The Stability in Waves Committee

Final Report and Recommendations to the 29th ITTC

1. INTRODUCTION

1.1 Membership and Meetings

Membership. The Committee appointed by the 28th ITTC consisted of the following members:

Dr. V. Belenky, (Chairman)
Carderock Division, Naval Surface Warfare Centre (NSWCCD), USA

J.-F. Leguen, (Secretary)
DGA Hydrodynamics, France

Dr. S. Cho
Korea Research Institute of Ships and Ocean Engineering (KRISO), South Korea

A. Matsuda
Japan Fisheries Research and Education Agency, Japan

Prof. J. Lu
China Ship Scientific Research Center (CSSRC), China

Dr. P. Feng
Marine Design & Research Institute of China (MARIC), China

Dr. Adriana Oliva-Remola (until May 2019)
Universitad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros Navales (ETSIN), Spain

Prof. E. Boulougouris
University of Strathclyde, United Kingdom

Meetings. Four Committee meetings were held as follows:

University of Madrid, Spain, March 2018
Kobe, Japan, September 2018
DGA, Val de Reuil, France, June 2019
A fourth meeting was planned at NSWCCD, Washington D.C., U.S.A., in March 2020 but was replaced due to COVID-19 by a series of video meetings (every two weeks) from March 2020 to March 2021.

1.2 Tasks From The 28th ITTC

The Stability in Waves Committee covers the stability of intact and damaged ships in waves. For the 29th ITTC, the modelling and simulation of waves, wind and current is the primary responsibility of the Specialist Committee on Modelling of Environmental Conditions, with the cooperation of the Ocean Engineering, the Seakeeping and the Stability in Waves Committees.

In the following, the Tasks received from the 28th ITTC are recalled for reference:

TOR 1: Update the state-of-the-art for evaluating the stability of ships in adverse weather conditions, emphasizing developments since the 2017 ITTC conference. The committee report should include sections on:

a) the potential impact of new technological developments on the ITTC,
b) new experimental techniques,
c) new benchmark data.
d) the practical applications of computational methods to prediction and scaling,
e) the need for R&D for improving methods of model experiments, numerical modelling,
f) include wind and current effects on stability assessments (intact and damaged ship, experimental and numerical methods),
g) review the effect of flooding on nonwatertight bulkheads due to fire fighting for example.

TOR 2:Review ITTC Recommended Procedures relevant to stability, including CFD procedures, and:

a) identify any requirements for changes in the light of current practice, and, if approved by the Advisory Council, update them,

b) identify the need for new procedures and outline the purpose and contents of these.

TOR 3: Review the IMO 2nd Generation Intact Stability Criteria and standards with a particular focus on the physics and background for each of the stability failure modes. It may be useful to develop a fault tree to better identify each of the stability failure modes.

TOR 4: Provide a recommendation on developing a procedure, or a set of procedures, for the direct assessment (computational methods) of the IMO 2nd Generation Intact Stability Criteria five modes of intact stability failure.

TOR 5: Review the state-of-the-art (both the experimental and the numerical studies) for free roll decay, forced rolling and excited rolling tests. Include methods of analysing time histories of data obtained from such tests and ways of deriving roll damping coefficients. Liaise with the Specialist Committee on Combined CFD/EFD Methods, as required.

TOR 6: Update Procedure 7.5-02-07-04.5 to "Numerical Estimation of Roll Damping", giving detailed guidance on how to carry out real or numerical model tests (e.g. free roll decay, forced rolling and excited rolling tests).

TOR 7: Updating the guideline 7.5-02-07-04.3 for the prediction of the occurrence and magnitude of parametric rolling towards a procedure. Liaise with the Seakeeping Committee as required.

TOR 8: Update Procedure 7.5-02-07-04.4 Numerical Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas, to include the complete 6-DoF equations of motion for a damaged ship and numerical methods for flooding based on more accurate hydraulic models (than estimated discharge coefficients).

TOR 9: Develop/suggest a method for estimating time to capsizing and/or sinking and include this in the report.

TOR 10: Continue the identification of benchmark data for validation of stability in waves predictions.

2. STATE-OF-THE-ART (TOR 1)

"Contemporary Ideas on Ship Stability - Risk of Capsizing" is a book recently edited (Belenky et al. 2019a). The book contains some of the most relevant papers from 2010 and 2012 presented at ISSW 2010-2011 and STAB 2012. The papers have been updated by their authors for the book. Most of those papers where referenced in previous ITTC reports in their original form. The up-to-date versions included in the book to be utilized from now on. The book is subdivided into four major parts: Mathematical Model of Ship Motions in Waves / Dynamics of Large Motions / Experimental Research / Requirements, Regulations, and Operations.

2.1 Potential impact of new technological developments on the ITTC (TOR 1 a)

During this period significant technological innovations have demonstrated the feasibility of active intervention in cases of flooding accidents on ships (beyond the counter-flooding of spaces). Although patents and concepts had proposed for several decades now, it is only recently that demonstrable systems have been developed. Special consideration should be given in the case of active buoyancy and stability recovery systems using inflatable devices (Chodankar, 2016; Zilakos and Toulios, 2018) and highly expandable foam (Vassalos et. al., 2016). Their underlying principle is to reduce significantly the permeability of the damaged space following an accident and regain partially the lost buoyancy. For such systems, it is crucial to capture accurately their impact on the floatability and the stability of the ship throughout the course of the event. This is equally important for their design and their actual deployment following the event. In this respect, they require accurate numerical simulation of the flooding process, considering as much as possible, all the contributing factors. Hence, numerical simulation codes that model correctly the timing and geometry of the inflation/expansion, the impact of the flood water pressure and air pressure build up due to potential blockage of the room vents, the impact of the position of the vessel (heel and trim) to the inflation/expansion process and any potential asymmetries resulting from them, are important integral parts to the design and operation of such systems. It should be noted, that although their impact on the survivability of the vessel can be significant, they are not covered under the existing SOLAS regulatory framework. Therefore, their developers are utilising the opportunity offered by the IMO's Circular, MSC.1/Circ.1455.

2.2 New experimental techniques (TOR 1 b)

Zhu et al. (2018) performed model grounding experiments in a water tank to study the coupling effects of both internal mechanics and external dynamics (see Figure 1). The influence of surrounding water on ship motions during grounding is taken into account. During their testing, varying rock penetrations are considered to study the grounding damage. Experimental results such as the horizontal grounding forces and damage extents are measured and analysed. The results show that the grounding damage depends on the rock penetration, and the surrounding water of the ship model has a big influence on the grounding damage assessment.

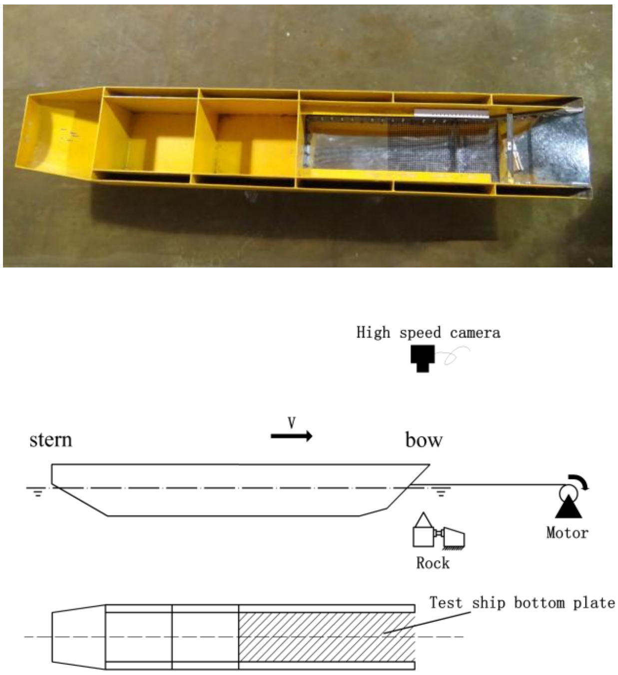


Figure 1: Experimental set-up for grounding from Zhu et al. (2018)

Hashimoto et al. (2019) designed and constructed a purpose-built device to obtain high-quality experimental data of roll decay motions for the quantitative validation of CFD methods. A certain initial heel angle was given to the ship model via the long square pipe as shown in Figs. 2 and 3. The square pipe can freely move in heave and pitch directions even when being held, thus, the change of ship attitude owing to the change of underwater ship volume and buoyancy balance is allowed. To start the roll decay test, the heel constraint is released momentarily by very swiftly open the aluminium frame through the strong tension of the connected rubber rope. As the rolling energy is consumed during the consecutive swings, the square long pipe will not reach the initial angle, thus will never hit the apparatus (see Figure 2 and Figure 3).

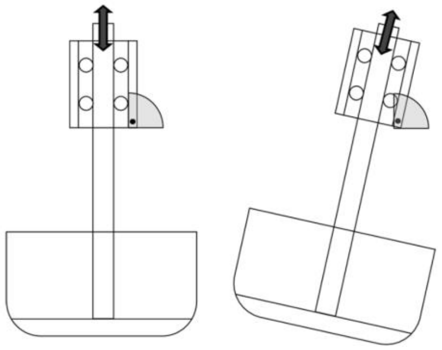


Figure 2: Schematic view of the apparatus

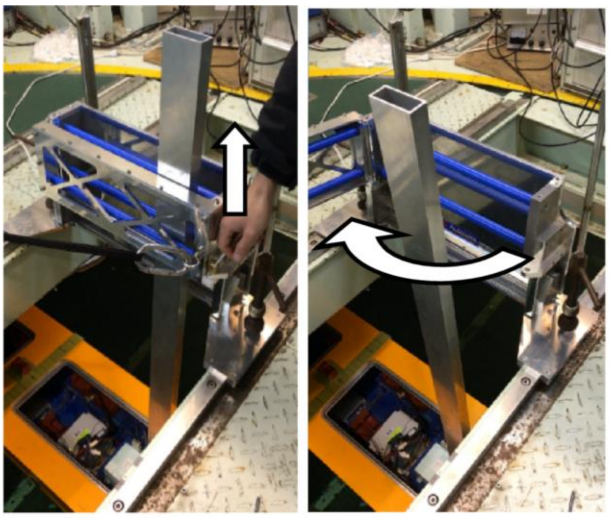


Figure 3. Opening mechanism of apparatus

Tsukada et al. (2017) and Ueno et al. (2019) have developed a wind loads simulator (WiLS) that enables us to carry out free-running model tests for investigating wind effects on ship performance (see Figure 4 and Figure 5). WiLS provides a free-running model ship with simulated wind loads taking into account the supposed true wind speed and direction, and instantaneous model ship speed, drift angle, and heading angle. It does not generate environmental wind but exerts forces and moment on a model ship using three pairs of duct fans. A control PC calculates time-varying longitudinal and lateral wind forces and yaw moment using wind loads coefficients estimated beforehand and ship motion data, and distribute them to the three pairs of duct fans. Feedback control ensures the intended wind loads using data from load cells on which the duct fans are mounted and those from accelerometers for correcting inertia forces of the duct fans.

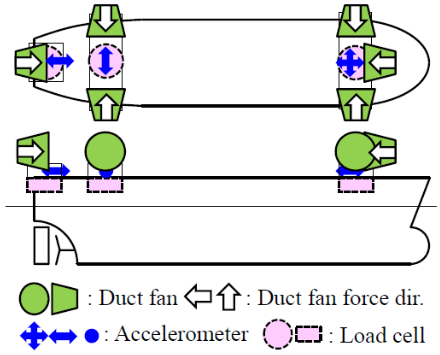


Figure 4: Configuration of onboard part of the wind loads simulator.

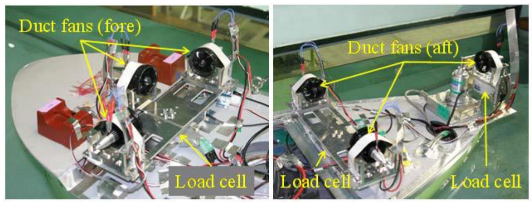


Figure 5: Wind loads simulator on a model ship

Asgari et al. (2020) investigated the Instantaneous Rotation Centres (IRC) and Most Often Instantaneous Rotation Centres (MOIRC) behaviour during the free roll decay tests of an FPSO by following the time series of the IRC. A static pure couple is applied to the hull to initiate the rolling. The motions during the test were tracked by an optical system using two Qualisys cameras, which measures the trajectory of the model, calculates the velocities, and transfer them into the non-inertial body-fixed coordinate system with the origin at the centre of gravity (see Figure 6). It is demonstrated through the experiment that IRC behaviour leads to distinct damping values. Two categories of IRC locus were devised according to observations. Category-I corresponds to a tangent type IRC locus. Category-II corresponds to a double parabolic IRC locus. The effect of the MOIRC on roll damping explains why the damping is different from the clockwise to the counter clockwise oscillation.

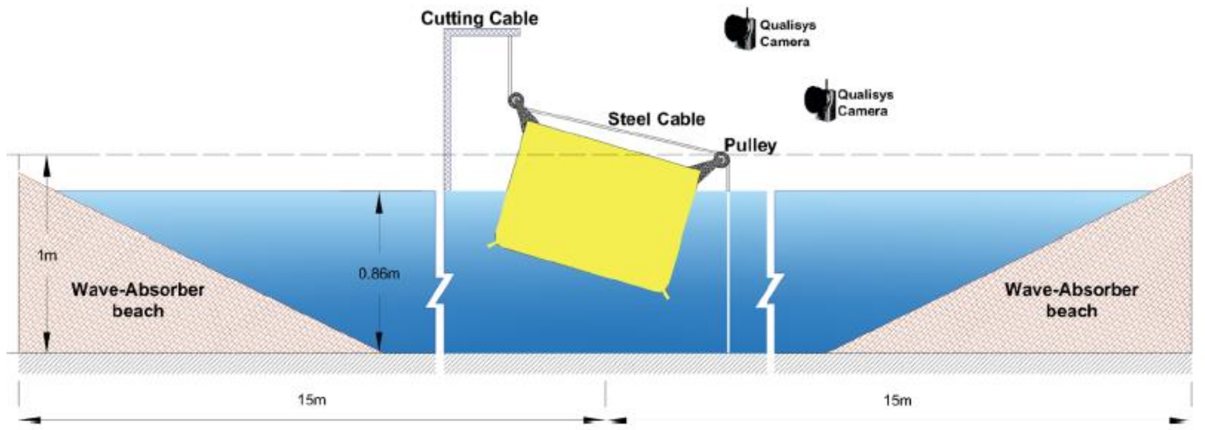


Figure 6: Motions track optical system, from Asgari et al. (2020)

2.3 Benchmark Data (TOR 1 c)

Only very few new benchmark data was identified. Three references of the numerical benchmark were added to the list, one from NSWCCD, Telste and Belknap (2008), about wave induces forces and moment, the second about roll damping, Irkal et al. (2019), and the last about CFD prediction of wave-induced forces on ONR-tumblehome hull form running in irregular stern quartering seas to study surf-riding/broaching, Hashimoto et al. (2018).

2.4 Practical applications of computational methods to the prediction of stability in waves (TOR 1 d)

Mizumoto et al. (2018) apply the system identification technique using a limited number of time histories from CFD in waves for broaching prediction. By applying system identification to wave forces from CFD, the broaching phenomenon observed during experiments was well predicted, and the broaching probability estimation in stationary irregular waves is also improved.

Htet et al. (2018) investigate the effect of the above-waterline hull shape on broaching danger in irregular stern-quartering waves, showing that the tumblehome vessel has a larger broaching probability because of its small calm-water resistance and small calm-water damping coefficients in the sway and yaw directions. It is also demonstrated in the paper that rudder gain plays an important role in the occurrence of broaching.

Sakai et al. (2017) studied quadratic equation describing zeros of Melnikov function leading to deriving a formula for the RPS value, corresponding to the second threshold of speed where surfriding occurs at any combination of instantaneous velocity and position on the wave.

Silva and Aram (2017), Aram and Silva (2019) applied regression to extract hydrodynamic derivatives from a simple double-body RANS simulation of drift and rotating arm tests. Araki et al. (2019) used a system identification technique to extract these derivatives from the simulated free-running test.

Meister et al. (2021) present several predictive modelling techniques that were used to investigate if parametric roll leading indicators can possibly be identified in the early stage design to avoid parametric roll resonance. They utilize four predictive models trained by the parametric roll data created through the execution of a nonlinear non-homogenous damped Mathieu equation, facilitating the prediction of parametric roll in early-stage design.

Sakai et al. (2018) applied an averaging method for evaluation of amplitude (with the super-harmonic effect) and critical speed of parametric roll in oblique waves without fitting calm water-$\overline{GZ}$ curve.

Sakai et al. (2019) calculated the encounter wave period for the Grim effective wave (Grim, 1961) to be used is the assessment of the amplitude of parametric roll.

Bu and Gu (2020) describe a combined numerical model of parametric roll and water sloshing in tanks. A potential flow solver was used for parametric roll, while CFD was employed for sloshing. As could be expected, sloshing may prevent the parametric roll from development.

Ma et al. (2018) performed the experimental and numerical study of the ship parametric rolling in regular head waves under different incident wave steepness for the C11 containership under two different drafts. Both the potential flow based on the nonlinear strip theory and viscous flow CFD method is used. It is found that the numerical results obtained by the CFD method give better results at larger incident wave steepness, especially for 0.05-0.07. It is concluded that it is necessary to consider the contribution of the radiation/diffraction force on the hydrodynamic restoring moment at large wave steepness in the case of the potential flow model if better numerical accuracy is desired.

Li et al. (2018) explore the influence of speed and course on ship parametric roll by using numerical and experimental method. Their results show that parametric roll will occur in bow waves when the encounter frequency is about twice the natural roll frequency, and the amplitude is equivalent to those in longitudinal waves. With the increase of wave height, the range of speed in which parametric rolling occurs will also expand.

Lindroth et al. (2019) point out that the stability at intermediate flooding stages has previously been ignored for cargo ships, but if the ship is equipped with cross-flooding devices, intermediate filling phases should be evaluated. Time-domain flooding simulation is used for a realistic assessment of intermediate stages and the actual time-to-flood, which enables realistic assessment of flooding progression and damage stability during these intermediate stages, while design improvements can be focused on factors that affect damage stability, such as efficient cross-flooding arrangement.

Yu et al. (2019b) investigates the influence of GM on surf-riding and broaching of the ITTC A2 fishing vessel using a time-domain 6-DoF numerical model. Through numerical simulations in following and quartering seas with different GM values, it is found that GM value has a significant influence on the occurrence of broaching and capsizing.

Begovic et al. (2018) verify the surf-riding/broaching vulnerability criterion of semi-displacement hull form of Systematic Series D, where the influence of the diffraction component on the wave surging force has been analysed. It is found that the limit Froude number for the considered hull form series is increased by improving the accuracy of 2nd level calculation, taking into account only nonlinear wave celerity or diffraction component and linear wave celerity.

Wang et al. (2018) explore the effect of propeller thrust reduction on ship's surf-riding and broaching events using a 6-DoF weakly nonlinear unified seakeeping-manoeuvring model. The effect of wave orbital velocity and the propeller submergence depth are considered in the numerical model. It is shown that propeller submergence ratio decreases and propeller thrust drops dramatically when surf-riding happens.

Gu et al. (2018b) compare the experimental results, using a 1/51 scale model of the 5415 frigate hull in a damaged condition, with CFD calculations. They investigate the impact of ingress and egress of floodwater and the interaction between the ship behaviour and water surface effect have on the ship motions and loads acting on the ship.

Begovic et al. (2017) comment that the CFD methods can predict the roll damping coefficient of a damaged ship in roll decay tests, reasonably well but the period of oscillations differs from the one measured in the model experiments. This has been observed also by Gao et. al. (2011, 2013). Furthermore, they note the significant challenge posed by the high computational time, which renders such methods impractical for common design practice. Furthermore, they conclude that the accuracy of the prediction is highly depended on the quality rather than the quantity of the mesh. They find the hexahedral trimmed mesh better than the hybrid (polyhedral and trimmed) and they recommend a time step less than the 1/100 of the phenomenon period, suggested by ITTC procedure 7.5-03-02-03 (Practical Guidelines for Ship CFD Applications, 2011).

Ruth et al. (2019) present the opportunities and challenges of using CFD for simulating the damage stability of cruise ships in waves, based on the experience gained in the joint industry project eSAFE.

Gu et al. (2017) conducted a model experiment with a tumblehome vessel for surf-riding and broaching in following and stern-quartering waves. Four types of ship motions with periodic motion, stable surf-riding, broaching and capsizing due to broaching were observed in the model experiment while broaching was observed three times in one wave case. The results between the vulnerability criteria calculation and the model experiment were compared to verify the feasibility of vulnerability criteria for the tumblehome vessel.

Gu et al. (2018a) studied the free roll decay motions of different scales under different initial roll amplitudes are simulated using one two-dimensional ship section, and the influence of scale effect is considered. It is found that the effects of different scales mainly due to the bilge keels, and scale ratio could affect the free roll decay motion and the roll damping coefficients, especially for large initial roll amplitude.

Gu et al. (2019) studied several crucial factors for CFD simulations, such as boundary condition, wall function, mesh quantity and quality. The influences of bilge keels on roll damping are also studied, several questions related to the CFD simulation of roll damping are discussed and the suggestions for the simulation are also proposed.

Gu et al. (2020) tried to parametric rolling in irregular oblique sea using a three-dimensional hybrid panel method. It was concluded that 3DOF model (heave-roll-pitch) produces more conservative results compare to 6-DOF model.

Lu et al. (2016) investigated the effect of parametric roll on added resistance in regular head seas. A formulae was developed based on Maruo theory that takes into account influence of parametric roll on added resistance.

Lu et al. (2017) carried out free-running experiments with partially restrained model in head seas. Tests were complemented by numerical simulations. It was found that the surge effect on parametric roll is generally small, the heave and pitch motions can have subharmonic components, and the radiation and diffraction effect on restoring variation can result in more conservative prediction.

Umeda et al. （2019) concluded that sway and yaw motions affected the capsizing of the actual ship in stern quartering waves due to pure loss of stability.

Lu et al. (2019) studied a surge-heave-pitch-roll coupled equation for predicting pure loss of stability in following seas. It considers a variable forward speed. Heave and pitch motions were computed by a strip method with an enhanced integrating method. This approach can appropriately estimate pure loss of stability in following seas as it was experimentally verified using the ONR tumblehome configuration.

Lu et al. (2020) studied a 6-DOF model for predicting parametric roll in stern quartering seas. Horizontal motions were modelled using MMG method (Yasukawa and Yoshimura, 2015). The study confirmed the hypothesis (Kubo et al. 2012; Umeda et al. 2019）that coupling with sway and yaw motion is an important factor for capsizing due to pure loss of stability.

Bu et al. (2019b, 2019c) conduct systematic researches on the effects of the radiation and diffraction forces on the roll restoring arm ($\overline{GZ}_{RD}$) under different heeling angles and wave amplitudes. The $\overline{GZ}_{RD}$ values are calculated by the integral of instantaneously average wetted surface and instantaneously wetted surface, separately. They find that the $\overline{GZ}$ consists of two important harmonic components in head waves and $\overline{GZ}_{RD}$ is the main contribution of the second harmonic component. Therefore, $\overline{GZ}_{RD}$ should not be ignored in head seas. Furthermore, they investigate the effects of $\overline{GZ}_{RD}$ on the prediction of the parametric roll. All the hydrodynamic forces are calculated by integrating wave pressure up to the wave surface based on the three-dimensional mixed source method. They find the body exact method can provide more accurate calculation accuracy compared with the commonly used body linear method.

Bu and Gu (2020) propose a nonlinear time-domain unified viscous and potential prediction method for the prediction of the time domain damaged ship motion coupled with damaged ship flow, in which the nonlinear three-dimensional time-domain hybrid source method is used for the simulation of damaged ship motion and the fully viscous method is used for the simulation of damaged ship flow. Two boundary conditions and two-time scales are used for the match between potential theory and viscous theory. The research shows that the proposed unified prediction method can predict the damaged ship motion and describe the details of damaged ship floodwater very well, at the same time, the calculation time can be saved a lot compared with the full viscous method as the mesh quantity for viscous simulation is considerably reduced.

Hu et al. (2019) proposed the capsizing probability calculation method for the dead ship condition. It is based on 1-DoF equation and Monte-Carlo simulation, as well as time-domain potential theory. Among this, the nonlinear righting lever $\overline{GZ}$ curve solution is obtained by two methods, one is the real-time calculation, the other subjects the influence of damaged tanks on the hull shape down to the wind and wave, thus combining combines the flooding process in the time domain of damaged ships with the capsizing probability research.

The roll damping and nonlinear roll restoring moment are important factors for the accurate prediction of both the onset and the amplitude of parametric roll. Yu et al. (2019a) conducted the quantitative prediction of the parametric roll of a KCS containership using a 5-DoF model to investigate the influence of different methods for nonlinear restoring moment and roll damping. Through comparison with model experiments, it was found that the accurate estimation of pitch motion is vital for the quantitative prediction of the parametric roll. The model considering only the nonlinearity of restoring forces caused by the instantaneous position of the ship with the wetted surface extending up to the still water level is found to be the most suitable restoring model for the quantitative prediction of the parametric roll. For cases close to the onset threshold of the parametric roll, the influence of roll damping can be dramatic.

Yu et al. (2018) proposed a detection algorithm based on Incremental Real-time Hilbert–Huang Transform (IR-HHT) to conduct early detection and advance warning of parametric roll in regular and irregular seas. Then, it was validated through free running model experiments that the detection algorithm can successfully detect the occurrence of parametric roll under different cases when the roll amplitudes are still small. Moreover, it was confirmed that the rudder anti-roll action after the detection can successfully stabilize parametric roll in regular and irregular head waves especially when the ship's speed is high.

Zhou (2019) conducted a further validation study of a hybrid prediction method of the parametric roll, using experimental results of two container ships and one Ro-Ro ship. This hybrid prediction method uses direct CFD approach to estimate roll damping coefficients, as well as a weakly-nonlinear model to predict 3-DOF motion responses. The upper limit wave steepness and parametric roll amplitude which can obtain satisfactory simulation have been investigated. On the other hand, this hybrid method is also found not applicable for simulating cases with strong nonlinearity like slamming, shipping-water and rudder-emergence.

Wawrzynski (2018) used a 1-DoF mathematical model to study the bistability and accompanying phenomena of rolling. A novel expanded form of the roll spectrum is proposed where bistability areas and the bistability origin point are included. The presented approach to the bistability phenomenon and amplitude jumps as to the bifurcation phenomenon can be used in the explanation of notable divergences between the results of numerical simulations for rolling with large amplitudes at resonance frequencies.

Kianejad et al. (2018b) adopted a CFD approach based on harmonic exciting roll motion (HERM) technique to compute the roll motion characteristics and damping coefficients in different conditions. The impact of appendages, Froude number and DoF on roll motion characteristics and damping coefficients are investigated for model-scale as well as full-scale to study the scale effects.

Kianejad et al. (2020) performed experimental and numerical simulations at beam sea condition to investigate the behaviour of roll restoring moment variations. The ship model is excited by regular waves at different heights and frequencies to measure the motion characteristics and the restoring moment in dynamic conditions. The results show that the restoring moments in the dynamic condition have significant differences compared to the static condition. The magnitude of restoring moment in the dynamic condition is measured based on the variation of heave motion of the model and the location of the wave's crest and trough with respect to the model. The proposed method can be applied to other types of vessels to calculate the restoring moment in regular and irregular waves and increase the accuracy of dynamic stability investigation.

Shigunov (2019) estimated stability failure rate from simulated ship motion records by direct counting, considered and validated the applicability of Poisson process for the description of time dependence.

Reed (2019a) examined the requirements for the total duration of numerical simulation. In the linear regime, the extremes can be characterized, using the standard deviation of ship motions. In the nonlinear regime, the duration should be sufficient to fit an appropriate model for the tail of the distribution.

Wandji (2019) reviewed several probabilistic methods and applied these methods for large samples of parametric roll response and linear response with the same spectrum. Histograms of estimates for upcrossing rate, time to the first exceedance and time between the exceedances were obtained. Distribution of amplitudes and block maxima were estimated. The results were compared to FORM.

Smith T.C. (2019) formulated approaches and procedures for validation of statistical extrapolation methods based on large-volume simulation. Weems et al. (2018) described fast qualitative numerical simulation approach for such large-volume validation. The numerical simulation is based on the calculation of instantons submerged volume.

Weems et al. (2019b) describe an application of Envelope Peaks over Threshold (EPOT) method that was used as a background of proposed ITTC procedure.

Gong et al. (2020) considered the effect of nonlinear wave on extreme ship motions using sequential sampling algorithm developed by Mohammad and Sapsis (2018).

2.5 The need for R&D on improving methods for model experiments and numerical modelling (TOR 1 e)

The study of the stability of ships in a stochastic sea state is usually carried out by Monte-Carlo simulations, so as to determine the safe operating envelope. This approach may, however, be very time consuming when the treatment of the 6-DoF seakeeping problem is necessary and in conditions where nonlinear coupling between the vessel responses lead to loss of stability (e.g. parametric rolling, broaching). Choi et al. (2017) adopt the First Order Reliability Method (FORM) to define possible combined critical wave and wind scenarios leading to capsize and achieve the calculation of capsizing probability at a much lesser computational effort. Jensen et al. (2017) show that the FORM can be an efficient method for estimation of outcrossing rates and extreme value statistics for stationary stochastic processes, suitable for the bifurcation type of processes such as a parametric roll. Sclavounos et al. (2019) develop a new methodology for the modelling of the nonlinear responses and stability of ships in stochastic steep waves, where a state-space stochastic differential equation is derived for the states governing the vessel nonlinear responses and a linear Fokker–Planck partial differential equation is obtained for the joint probability density function of the vessel motions, allowing the direct evaluation of the joint probability density function of the responses via the solution of the Fokker–Planck equation.

Irregularity of waves may alter the physics of a stability-in-waves-related phenomenon. Results on the computation of celerity of irregular waves are reviewed in Spyrou et al. (2019). As the celerity of irregular wave is a stochastic process, the surf-riding state is not equilibrium – the point where the sum of all the forces is zero moves with acceleration. The domain of surf-riding in phase space is described by a Lagrangian coherent structure (Kontolefas and Spyrou, 2016). Kontolefas and Spyrou (2018) related the Lagrangian coherent structure with “high runs” (instantaneous speed above the normally expected fluctuations) and the estimated probability of surf-riding.

The ultimate objective of probabilistic methods is the estimation of the rate of exceedance of a large roll threshold. A long-duration numerical simulation represents a challenge due to computational cost; thus the estimate may need to be obtained without observing actual event being essentially a statistical extrapolation problem.

Consistent multi-fidelity modelling may provide accuracy close to a high-fidelity model with the computational cost of a low fidelity model. Besides the consistency between the models of different fidelity, quantification of uncertainty, which is the key issue, considered in Brown and Pipiras (2019).

Maki (2017) developed a method for estimation of the probability of instantaneous values of roll motions. First, the shape of the distribution is obtained by subjecting a dynamical system to white noise excitation; it is further scaled with variance estimate. Further study of the method, including application, comparison and experimental validation is described in Maki et al. (2018, 2019a, 2019b).

Macé et al. (2019) developed a method for estimation of capsizing probability by extrapolation of an estimate of roll exceedance rate.

Chai et al. (2018) compared path integration method (Kougioumtzoglou and Spanos 2014) with the averaging method (Dostal et al. 2012; Dostal and Kreuzer 2014) and formulated recommendations for application based on the advantages of both methods.

There are several probabilistic methods based on extreme value theory. The extreme value theory states that the largest value in a sample of independent identically distributed variables tends to Generalized Extreme Value (GEV) distribution (the first extreme value theorem also referred to as Fisher-Tippet-Gnedenko theorem). It also states that a distribution above some large threshold can be approximated with Generalized Pareto Distribution (GPD) - the second extreme value theorem, referred as Pickands-Balkema-de Haan theorem (see e.g. Coles, 2001).

Pipiras (2020) examined issues associated with using GPD for modelling extreme roll motions. While universal applicability of GPD follows from the second extreme value theorem, its practical use may be associated with significant statistical uncertainty including the appearance of the upper bound, related to the negative value of the estimate of the shape parameter. The appearance of upper bound may prevent the use of GPD for extrapolation if the target value is larger than the upper bound. Anastopoulos and Spyrou (2019a) found that while GPD works for large roll angle, it is not applicable for a description of escapes (capsizings). The issues of GPD may be resolved with "physics-informed model" where physical information is included into a statistical model in order to decrease the uncertainty (Glotzer et al. 2017).

Belenky et al. (2019a) proved that the response of a dynamical system with softening nonlinearity has a heavy tail of the distribution using a piecewise linear approximation of the restoring term. Belenky et al. (2018a) described a new version of EPOT using Pareto distribution to model a heavy tail. Belenky et al. (2018a, 2018b) described a new version of the split-time method using an exponential distribution for capsizing metric. Estimation of probability of capsizing caused by broaching with the split-time method is described in Belenky et al. (2017) and Weems et al. (2020) using an approximation of the boundary of Lagrangian coherent structures describing surf-riding states in irregular waves (Kontolefas and Spyrou, 2016; 2018).

The other group of methods is based on the critical wave group approach, where the extreme roll is estimated from a response to groups of large waves. Anastopoulos and Spyrou (2017) described further development of a realistic wave group model with a variation of amplitudes and periods (Anastopoulos and Spyrou, 2016). Initial conditions of a dynamical system upon the encounter of the wave group are treated in Anastopoulos and Spyrou (2019b). It describes a significantly more complete solution in comparison with the previous version (Themelis and Spyrou 2008). All the cited papers use Markov chain to model a wave group, originally proposed by Kimura (1980) and applied for probabilistic assessment of dynamic stability in waves by Themelis and Spyrou (2007).

Mohammad and Sapsis (2018) used a combination of an envelope of wave elevations and Gaussian-shape functions (Cousins and Sapsis, 2016; Farazmand and Sapsis, 2017) for detecting the wave groups. Adaptive sequential sampling was applied; the central idea is to use Gaussian process regression (GPR) that enables an optimization algorithm to drive the selection of critical wave groups that define the tail of the response distribution. The method offers sufficient computational efficiency to be used with advanced panel code (Stevens, 2018;

Rathore, 2019) and CFD (Mohammad and Sapsis 2018; Gong et al. 2020) to evaluate the extreme roll response.

While not using the concept of wave groups explicitly, the Design Load Generator (DLG) can be considered as a part of the wave group approach as it searches for a sequence of waves leading to an extreme response as a combination of random phases. Originally developed for the assessment of extreme wave-induced loads (e.g. Alford and Troesch, 2009), it was extended to extreme motions (Kim and Troesch, 2013; 2019). Xu and Maki (2018, 2019), Xu et al. (2020) integrated DLG with RANS solution, using FOAM.

2.6 Include wind and current effects on stability assessments (TOR 1 f)

Speed and direction of current are not parameters of stability, it is the relative transverse speed of the structure that is. When it is a fixed structure or when it is not in line with the ship, we can speak of drift or current. MSC.1/Circ.1200 explains the conditions of a test making it possible to determine the forces due to drift for a relative incidence of 90° which corresponds to the dead ship situation, a case where the current is a significant parameter. MSC.1/Circ.1227 gives an example of an application for a cruise ship. It is not indicated how to determine the speed of drift other than by searching by iteration for the value allowing to counter aerodynamic forces. Note that the indeterminacy of the equation system necessitates taking additional hypotheses such as the symmetry of the float for determining the point of application of the forces useful for estimating the heeling lever arm, or else using the same reduction point than during wind tunnel tests, generally taken at the waterline. Generally, the point of application of the drift forces is taken at half a draft under the waterline although it is rarely checked (see tests of the MSC.1/Circ.1227). A particular case is a gyration at high speed on calm water which can cause capsizing (some rules take into account a criterion related to this situation) but it can be treated in a complete and independent way by the field of manoeuvrability.

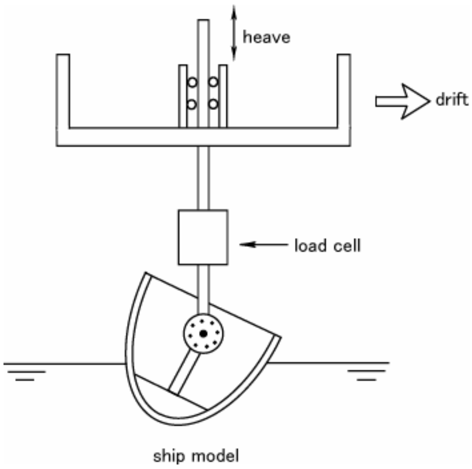


Figure 7: Set up proposed by IMO for hydrodynamic forces estimation due to current

Stability in waves committee recognizes the importance of wind. It is a strong parameter in the sense that different rules used a different way to take into account the wind (2008 IS code / NSC). Analysis of rules could be interesting to compare those rules. Stability in waves committee is interested to obtain the references for statistics of wind including nominal speed, vertical profile, speed spectrum and direction.

At this moment, stability in waves committee does not have an interest in data on currents and does not have plans to study current effects on the stability of either intact or damaged ships. Stability in wave committee is not specifically focusing on the stability of column-stabilized units beyond general state-of-the-art review. Potential interest in current is the similitude of current with the dead ship conditions when the ship is slowly drifting transversely by the action of wind (the drift speed and position of hydrodynamic forces are under questions in rules).

As it was pointed out by Francescutto (2015), so long as the wind was the propelling force for the ships, the master of a sailing ship was also aware at every moment of the approximate amount of the stability, because when sailing he constantly happened to perform some kind of inclining experiment with his vessel, even if it was primitive. It was therefore easy for the master to avoid imperilling the stability of his ship, and whenever he was tempted to load an excessive deck-cargo or otherwise reduce the stability, he probably did so well aware of the risk he was causing his vessel.

It is perhaps why obviously wind was pointed as a significant factor of risk of capsizing and then to stability checks. The first idea came by Pierrottet (1935), as mentioned by Francescutto (2015), and finally came out as the origin of the weather criterion. As explain by OMI in the explanatory notes to the international code on intact stability, 2008 (MSC.1/Circ.1281), the weather criterion firstly appeared in the IMO instruments as Attachment No.3 to the Final Act of Torremolinos International Convention for the Safety of Fishing Vessels, 1977 as an answer to a recommendation given in the conclusions of SOLAS'74. In the end, the Weather Criterion was adopted in 1985 as Res. A.562 even if it was already enforced in several countries including Japan, Russia and Australia. It is partly based on the Japanese stability standards for passenger ships as related by Tsuchiya (1975) and Watanabe (1956).

As mention by Francescutto (2015), weather criterion, however, in modern language is a (moderately) physical approach but it is not a risk-based approach. Results must be look in a whole, from the definition of loading case to the final results which are, for a particular ship, the vertical position of the centre of gravity. Intermediate parameters have not to be used as a physical input. In particular, as clearly write in the explanatory notes to IMO 2008 IS Code, the wind speed is not linked to a real condition. Only ships characteristics can be modified as, for example, the default value as the drag coefficient can be modified accordingly IMO's Circular, MSC.1/Circ.1227, where an experimental solution to determine the heeling moment and the vertical position of aerodynamics forces is proposed (see Figure 8).

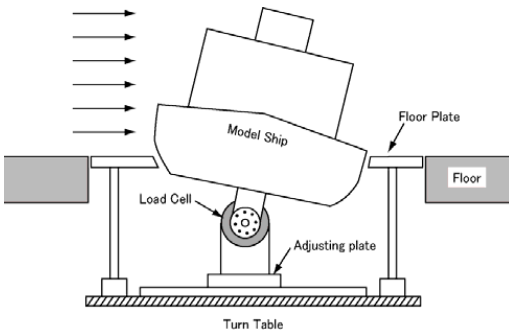


Figure 8: set up proposed by IMO for aerodynamic forces estimation

The methodology of weather criteria, in its entirety, only ensure that the initial populations (existing long before its adoption) used to establish it, is correctly separate in two-part, sure and more dangerous. The criteria were developed originally to guarantee the safety against capsizing for a ship losing all propulsive and steering power in severe wind and waves. It is a particular situation, one of the worst for a ship, and identified by OMI as one on the five failure modes, which is known now as a dead ship in the SGISC.

Even if the method must be considered as a whole, intermediate assumptions can be describe in order to be able to determine some possible improving.

As usually, the verification of the criteria must be done for all unfavourable loading cases, but, following the dead ship assumptions, only transverse relative wave heading at zero speed is taken into account. That means that it is assumed that the equilibrium of the ships is transverse to waves and that the wind is in the same direction. This strong assumption cannot be derogated easily.

The physics related to the wind is not taken into account with the same simplifications for all rules. Only some rules, even if it began to be generalised, consider the reduction of wind speed with the altitude from calm water, but no one's consider the shift in the direction against it. For some rules, as IMO one's, a gust factor is explicitly used to increase the wind speed. As explained before the wind speed, which is for a defined ship, the most important parameter cannot be related to the operational situation but because there is no physical relation with a real meteorological situation neither an estimation of a risk, it seems not be essential. For example for a ship, it is not allowed to determine the maximum speed by inversing the methodology (ship and characteristics fixed, varying wind speed to reach the criteria).

The variation of heeling moment with the heel angle is one of the most variable changes on various rules. Most of them are not justify then it is difficult to choose one even if some more physical solution is suggest nowadays on the base of experimental data in wind tunnel or by numerical calculations. Most of default values have physical sense and have be chosen in an objectives of simplification. For example the heeling moment is expected to be constant with heel angles for IMO standards rules but for most of naval rules a reduction is used. The true is certainly not one of the solutions but can be determined with appropriate experiments or simulations. Many propositions of modifications to improve some of the physical parameters where proposed as, for example by Brown and Deybach (1998). IMO Circ.1227 give the possibility to adjust the aerodynamically force and the point of application of aerodynamic and hydrodynamic forces using experiments results.

When one wishes to compare regulations which take into account wind in one or more of their criteria it is necessary to consider the complete methodology. It is also necessary to compare the regulations on the same final objective which is, for a given ship, the vertical position of the centre of gravity. For the same ship at a given displacement, it is therefore necessary to consider not only the wind speed of each of the regulations, but also all the parameters influencing the final result including also the treatment of the $\overline{GZ}$ curve to obtain the criterion. The regulation using the strongest wind speed will not necessarily be the most conservative regulation in the end if other assumptions are less severe. A mix between the parameters is possible. We can thus create regulations, for educational purposes, very severe or very optimistic. Following an example of this type of comparison for the weather criteria (unpublished work following Luquet et al, 2015), red points are full rules, blue mix of them and black extreme fictive rules.

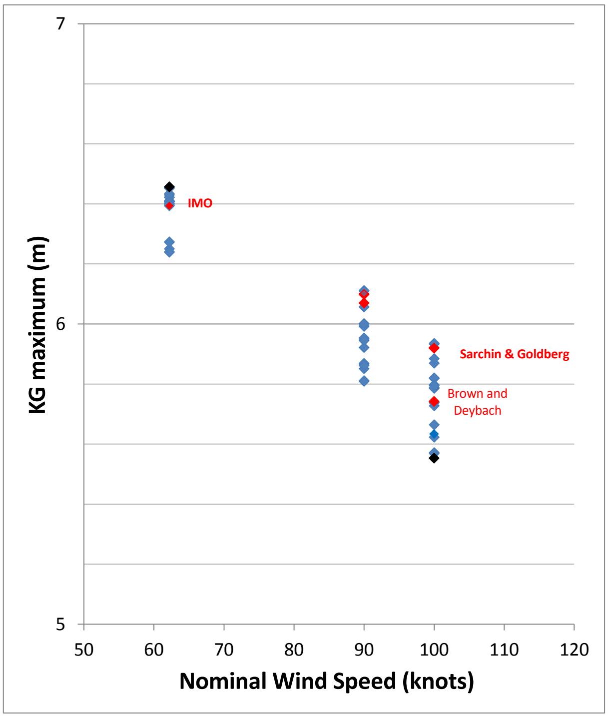


Figure 9: *KGmax* due to wind for a set of rules

2.7 Review the effect of flooding on non-watertight bulkheads due to firefighting (TOR 1 g)

Ruponen (2017) addresses this very important issue that may affect the intermediate stages of flooding and lead to asymmetries and potentially make the vessel more vulnerable to capsizals. It builds on the knowledge gained from a series of full-scale tests on leakage and collapse of various non-watertight structures carried out at CTO in Gdansk, Poland for the EU FP7 project FLOODSTAND (2009-2012) (Jalonen et.al., 2012). The test methodology and an analysis of the results on the leakage and collapse of non-watertight ship doors is presented in detail in Jalonen et al. (2017). A similar study on the leakage and collapse of non-watertight doors has been presented by Dankowski et al. (2014). They are all stem from the fact that modern passenger ships have complex transverse and vertical fire protection subdivisions. Many of them are not watertight. However, their presence may have a significant impact on the flooding process. This can be addressed by time-domain flooding simulation, combined with the latest research on the leakage and collapse of non-watertight structures. Ruponen (2017) has shown that the status of those non-watertight doors can have enormous effects on the progress of flooding, and particularly on the time-to-capsize (TTC). In contrast, the variation of the modelling parameters for the leakage and collapse of the closed doors had much smaller effects. Therefore, Ruponen (2017) proposes the following conservative approach for the door statuses in time-domain damage stability simulations: (a) the fire doors at the staircases and escape trunks that allow up and down-flooding, and all doors on the bulkhead deck could be considered as open; (b) the doors in the longitudinal bulkheads under the bulkhead deck should be considered as closed.

3. REVIEW ITTC RECOMMENDED PROCEDURES (TOR 2)

3.1 Introduction

In the following, some explanatory comments are given about the updating activity of the eight procedures reviewed and the six new procedures proposed.

3.2 Updated procedures (TOR 2 a)

Procedure 7.5-02-01-08 (Single Significant Amplitude and Confidence Intervals for Stochastic) is currently under responsibility of the Quality Systems Group. The procedure uses different algorithms for a large and small number of runs. Their unresolved issue of small-number of the run algorithm is the “cut-off” point for the autocorrelation estimate (equation 9 of the procedure 7.5-02-01-08) – it may be too large for a long record, containing a large number of points. Levine et al. (2017) proposed to identify the “cut-off” as a decorrelation time when the autocorrelation drops below 0.05. Pipiras et al. (2018), Weems et al. (2019a) considered the “cut-off” based on error minimization, using long-run variance (Lu and Park, 2019). The “cut-off” point issue is still pending. Upon its successful resolution, it will make sense to update the procedure 7.5-02-01-08. Unifying the algorithms for a small and large number of runs also may be considered. Quality Systems Group is expected to take a lead on such an update.

Procedure 7.5-02-05-07 (Dynamic Instability Tests from high-speed marine vehicles domain) was reviewed and no change is proposed by the committee.

Procedure 7.5-02-07-04.1 (Model Tests on Intact Stability) was reviewed and no change is proposed by the committee.

Procedure 7.5-02-07-04.2 (Model Tests on Damage Stability in Waves). The procedure was submitted by the previous Stability in Waves committee. No comments were received by previous and actual committee no improvement is requested by this committee.

Procedure 7.5-02-07-04.3 (Predicting the Occurrence and Magnitude of Parametric Rolling) was submitted. A three-level structure was adopted for the procedure, similar to the second-generation IMO intact stability (MSC.1/Circ.1627). Each level describes methods of prediction of different fidelity and thus complexity. The appropriate level is chosen by the user depending on the required prediction fidelity. The first-level predication is based on analytical and semi-analytical formulae. The second level prediction is a simplified numerical method. The third level prediction presumes using advanced numerical code. The procedure contains recommendations on specific issues, related to the assessment of parametric roll in irregular waves. The list of references has been updated.

Procedure 7.5-02-07-04.4 (Numerical Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas) was submitted. TOR 9 "Develop/suggest a method for estimating time to capsizing and/or sinking and include this in the report" will be answered in this procedure (see section 9). No other change is requested.

Procedure 7.5-02-07-04.5 (Numerical Estimation of Roll Damping) was reviewed and significantly updated by the committee; more detailed descriptions of the changes are summarized in section 7 of this report.

Procedure 7.5-03-02-03 (Practical Guidelines for ship CFD application) was reviewed and the committee proposes to modify Section 3.6. Time Step by adding the recommended time interval when an overset mesh is used, i.e., if an overset mesh is used, use at least 500-time steps per period.

3.3 News procedures (TOR 2 b)

Proposal for Guidance on Avoiding Self-Repetition Effect during Numerical Simulation of Ship Motions was submitted. Purpose of the Guidance is to formulate a process for verification of the absence of self-repetition effect and statistical validity of irregular waves in numerical simulation of ship motions. Currently used a mathematical model of irregular waves is based on work of St. Denis and Pearson (1953) and Longuet-Higgins (1962). Application of this model in time-domain numerical simulation requires discretization of the spectral density of wave elevations. An inappropriate choice of frequency discretization of the spectrum may lead to self-repetition effect, compromising statistical validity of the model. It may result in an incorrect assessment of statistical uncertainty of SSA and other estimates as required by procedure 7.5-02-01-08. The Interim Guidelines for the Second Generation IMO Intact Stability Criteria requires that modelling of irregular waves should be statistically and hydrodynamically valid and self-repetition effect should be avoided (Paragraph 3.3.2.1.2 of Annex of MSC.1/Circ.1627). To verify the absence of the self-repetition effect the auto-covariance function will be computed directly from the spectrum, using the chosen frequency discretization. The autocovariance of a statistically and hydrodynamically valid mathematical model of irregular waves should show no correlation beyond the initial decay. Theoretical background for the proposed Guidance is available in Belenky (2011).

Proposal for Computational Procedure for Predicting the Instantaneous $\overline{GZ}$ Curve during Time-Domain Numerical Simulation was submitted. Purpose of Procedure is to describe a process for computation of the instantaneous $\overline{GZ}$ curve in irregular waves to enhance the analysis of large roll angles. While the computation of stability curves in regular waves is wildly available from commercial software, similar capability for irregular waves is rare. At the same time knowing the form of the instantaneous $\overline{GZ}$ curve in irregular waves may help to explain large roll excursions, see Figure **10**. Calculation of the instantaneous $\overline{GZ}$ is fairly straightforward: for each time step of the calculation, the ship is heeled through a range of angles relative to its predicted position, the forces and moments on the ship are computed for the heeled position, the ship's heave position and pitch angle, expressed relative to a global coordinate system, are iteratively adjusted until the dynamic equilibrium in these modes is achieved, finally, the net roll moment defines the instantaneous $\overline{GZ}$ value. Theoretical and numerical background for the proposed procedure in available in Belenky and Weems (2008).

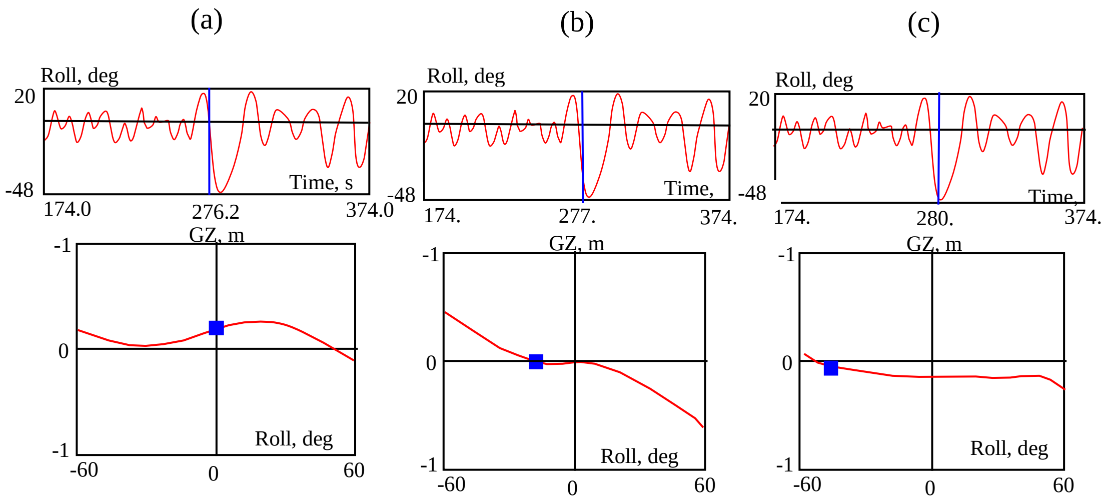


Figure 10: Time history and evolution of $\overline{GZ}$ curve in irregular waves a) zero roll angle; b) zero stiffness; c) Roll angle excursion

Proposal for Procedure Inclining test was submitted. The task done have started by an analysis of the many similar procedures written by the classification societies or standardisation offices. The most complete of those seem to be the ones from the American Standard taking into account several types of vessels. As requested, focus on uncertainty was performed, for example, suggesting a checklist in order to be sure that all precautions have been taken. It is also suggested to performed roll period measurement at the same time in order to be able to make an operational estimation of the *GM* as recommended by IMO.

4. IMO 2ND GENERATION INTACT STABILITY CRITERIA (TOR 3)

The task 3 of the TOR contains the statement "… *it may be useful to develop a fault tree to better identify each of the stability failure modes*".

Current international stability regulations are collected have been established from the International Code on Intact Stability 2008 (2008 IS Code). The Code was adopted by resolution MSC.267 (85) of the Maritime Safety Committee (MSC) of the International Maritime Organization (IMO) and came into force in July 2010.

Stability criteria intended for all types of ships can be found in two sections of the Code: requirements for $\overline{GZ}$ curve in section 2.2, and severe wind and rolling criterion (also known as the weather criterion) in section 2.3. The criteria from section 2.2 have originated from works by Rahola (1939), which is embodied in Res. A.167 (ES.IV). The work on the weather criterion that commenced in the 1950s (Kobylinski and Kastner, 2003) is embodied in Res. A.749 (18). The Code recognizes that the fleet is evolving and the Code "should not remain static" (paragraph 2 of the Preamble). The Code also notes the variety of types of ship and complexity of physical phenomena involved in the stability analysis and recognizes that "...problems of safety against accidents related to stability have generally not yet been solved" (paragraph 2 of the Preamble). Directions for further development are formulated in Chapter 1 of Part A of the Code. Priority is given to the development of performance-oriented criteria for:

- Righting arm variation, resulting in parametric roll resonance and pure loss of stability (paragraph 1.2.1);
- Resonant roll in dead ship conditions (paragraph 1.2.2);
- Broaching and other manoeuvring related phenomena (paragraph 1.2.3).

There are totally four distinct modes of stability failure. The fifth mode of failure, excessive accelerations, was added, following the German proposal (SLF 53/3/2).

The intact stability working group of IMO Subcommittee on Stability and Load Lines and on Fishing Vessels Safety (SLF) was assigned this task. The working group was re-established in 2002 with the dual purpose of finalizing the 2008 IS Code and further development.

Performance-oriented criterion is essentially a mathematical model of the physical phenomenon “responsible” for possible stability failure. A new framework was envisioned to confront the complexity of these physical phenomena and avoid unnecessary costs of analysis performed on irrelevant cases. The criteria is defined a multi-teared (or multi-leveled) structure, where the first tier defines if the case is relevant, and the second tier determines the loading conditions and environmental conditions that are likely to lead to stability failure. The most advanced numerical techniques of analysis are to be used in the third tier. If a possibility of stability failure cannot be eliminated in a design stage, the information produced by the third tier analysis is applied to ship-specific operational guidance. This framework was formulated in a paper SLF 50/4/4, discussed on the 50th through 53rd sessions of SLF, taking the final form in Annex 1 of SLF 54/3/1.

During the intersessional period leading to SLF 55 and SLF 55th session, most of criteria were developed and agreed, in principle. The criteria for parametric roll and pure loss of stability were formulated as proposed amendments to part B of the 2008 IS Code (Annex 1 and 2 SLF 55/WP.3). Due to reorganization of some IMO sub-committees, the SLF Sub-Committee was amalgamated into the Sub-Committee on Ship Design and Construction (SDC) together with elements of the former DE Sub-Committee. During the intersessional period leading to SDC 1 explanatory notes for pure loss of stability and parametric roll was developed (Annexes 3 and 4 of SDC 1/INF.8). A text on draft amendments for surf-riding / broaching and dead ship condition was developed (Annexes 15 and 16 SDC 1/INF.8). The draft explanatory notes for dead ship condition (SDC 1/INF.6) and surf-riding broaching (SDC 1/5/4) is drafted and submitted. The first draft text of excessive acceleration was developed (Annex 33 of SDC 2/INF.10) during the intersessional period leading to SDC 2 and at the 2nd SDC session. The working group completed vulnerability criteria for pure loss, parametric roll and surf-riding, which were documented as Annexes 1 through 3 of SDC 2/WP.4

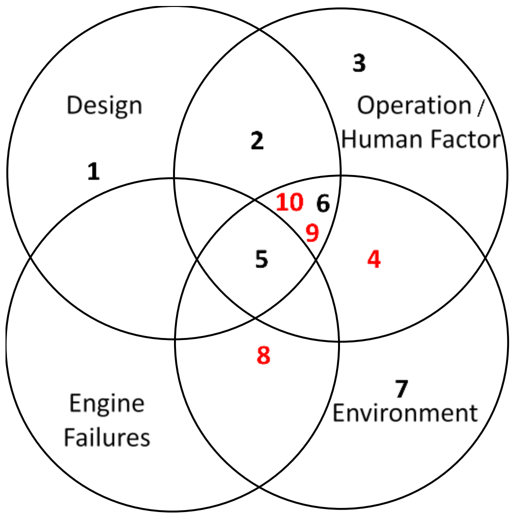
During the intersessional period leading to SDC 3 and 3rd SDC session, criteria for dead ship conditions and excessive accelerations were completed (Annexes 1 and 2 of SDC 3/WP.5 and SDC 3/INF.10). Explanatory notes for all failure modes documented and released as Annexes 3 through 7 of SDC 3/WP.5 and 16 through 20 of SDC 3/INF.10. Draft Guidelines on operational limitation were developed and documented in Annex 21 of SDC 3/INF.10. The intersessional period leading to SDC 4 and 4th SDC session focused on testing of the vulnerability criteria primarily with matrix calculations. Draft guidelines on direct stability assessment were documented (Annex 1 of SDC 4/WP.4).

The first draft complete of the complete Guidelines of the second generation intact stability was developed during the intersessional period leading to SDC 6 and 6th SDC session (SDC 6/WP.6). It was finalized during the intersessional period leading to SDC 7 and 7th SDC session (SDC 7/WP.6), approved and published by Maritime Safety Committee as MSC.1/Circ.1627. The completion of the explanatory notes is expected in early 2022 at the 8th Session of SDC.

Fault Tree Analysis (FTA) is a standard risk management tool, focusing on the safety-critical function of a complex engineering system. It models the development of a failure of the entire system based on different scenarios of failures of the elements of this system. A ship is considered as a system, including the ship itself, operator, and institutional policies. The system is subjected to various environments. A ship may have the following main scenarios for the end of her life: intact capsizing, capsizing due to damage (caused by collision or grounding, i.e. event not expected in the life of the ships…), structure collapse (due to environment or excessive loads), retirement from the service due to principle subsystem ageing and/or failure. As for a ship's end-of-life failure, the presentation in a format of a fault tree for some basic events may cause a failure to propagate through several brunches simultaneously. For example, collision damage could lead to damage stability failure and to further deterioration of structural integrity at the same time. Such interdependencies of branches usually are not considered within the FTA.

Most of these interdependencies are related to the environment. A loss of a ship is often a combination of many failures. Alman et al. (1999) refer to the letter by USN Admiral Chester W. Nimitz of 13 February 1945, summarizing the damage on the US fleet after crossing a typhoon (data that are the basis of the establishment of most of western navies rules, initiated by Sarchin and Goldberg in 1962). They mentioned, "*The most important is that in extreme seaway conditions, many things frequently go wrong at the same time or the worst possible times, leading up to a point where the crew are no longer take steps to save the ship. At this point the ship simply becomes a capsize 'waiting to happen*". As, a result, a conventional fault tree is not sufficient for a comprehensive presentation of the ship's failures.

The interdependences of the causes of failures are better presented with Venn diagram, the graph, shown in Figure 11, is a modification of one from Dahle and Nedrelid, (1982), see also Kobilinlsky and Kastner (2003). The Venn diagram in Figure 11 shows five modes of intact stability failure, covered by the second generation of IMO intact stability criteria (SGISC), corresponding to numbers 4, 6, 8 and 9.



1. When launched due to faulty design
2. Turning at high speed
3. Overloading
4. High speed in following sea – broaching and pure loss of stability
5. Bad weather + lack of knowledge + low stability + subsystem failure
6. Excessive water on deck
7. Heavy icing combined with heavy sea preventing clearing off the ice
8. Dead Ship Condition
9. Parametric Roll
10. Excessive Acceleration

Figure 11: Venn diagram of ship's stability failure mode

The Venn diagram in Figure 11 provides a relatively simple presentation for "big picture" of stability failures and modes of stability failures, covered by SGISC. A further consideration is focused on these five modes. The development does not include any consideration of loads (height, shift of, liquefaction…), limited by design, environment, engine failure and human factors.

The interdependency of basic events cannot be completely not avoided for even only SGISC modes of failure. For example, high speed in following or stern quartering seas may lead by surf-riding, following by broaching-to or (if a variation of $\overline{GZ}$ curve in waves is significant) to pure loss of stability.

Also, each ship is functionally different to a certain extent and a fault tree is uniquely reflecting ship type, operational practice, and environment (Alman et al. 1999). It may be difficult to generalize following all possible consequences in a format of a single fault tree.

Thus, each mode of failure will be described by one fault tree.

What is a stability failure? The following capsizing definition is available in SLF 54/3/1: "*capsizing is formally defined as a transition from a stable nearly upright equilibrium that is considered safe, or from oscillatory motions near such equilibrium, to another stable equilibrium that is intrinsically unsafe (or could be considered unacceptable from a practical point of view)*". However, capsizing is not mentioned in the final version of SGISC in SDC 7/WP.6; the stability failure is defined as:

The roll angle exceeds prescribed limit (paragraph 1.1.2.2.2 of MSC.1/Circ. 1627).
Heel and list exceeds a certain limit (paragraph 1.1.2.2.1 of MSC.1/Circ. 1627). It may be generated cargo shift and then dynamic stability extreme events.
Lateral acceleration exceeds a certain limit (paragraph 1.1.2.2.3 of MSC.1/Circ. 1627) give limit value for.

The relation between these modes of failure is clearly strong but its description is out of the scope of the present task, as it is not addressed by SGISG. Many papers try to link the capsizing probability and failure as the probability to exceeds roll angle, as Maki et al. (2018) or Macé et al. (2018) but more work is needed.

Figure 12 shows a fault tree for the stability failure caused by broaching-to, preceded by surf-riding. The surf-riding occurs in following or stern-quartering seas, in high speed, when a long and steep wave is encountered. While such long and steep wave usually overtakes a ship, it creates significant surging force. The surging force may be sufficient to accelerate the ship to forward speed, corresponding to wave celerity. Then a ship may surf-ride. The surf-riding essentially is a dynamic equilibrium where surging wave force added to thrust equal to resistance at wave celerity.

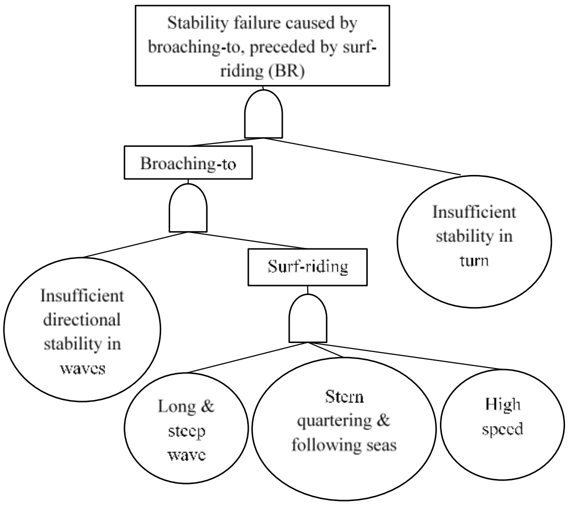


Figure 12: Fault tree for stability failure caused by broaching-to (BR)

A ship usually takes a position on the front slope of the wave, slightly pitching forward. The water flow around the hull and the rudder leads to decrease of directional stability of a ship. If the directional stability becomes insufficient, the ship makes a sharp uncontrollable turn.

If the stability of a ship is insufficient to withstand a moment of centrifugal force generated by the turn, a stability failure may develop.

Error! Reference source not found. shows a fault tree developed for the parametric roll. To occur, parametric roll requires encounter of several waves of similar length and height certain speed and heading. The frequency of encountering these waves should be about twice the natural frequency. This fulfils the frequency condition of the principle parametric resonance.

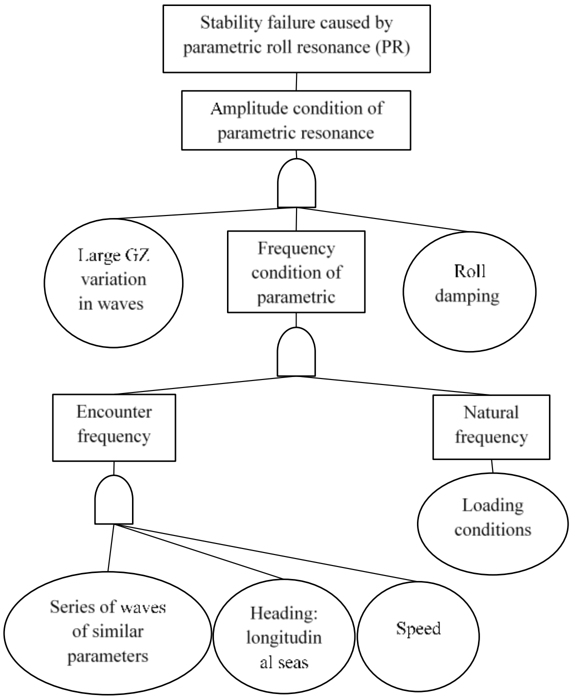


Figure 13: Fault tree for stability failure caused by parametric roll (PR)

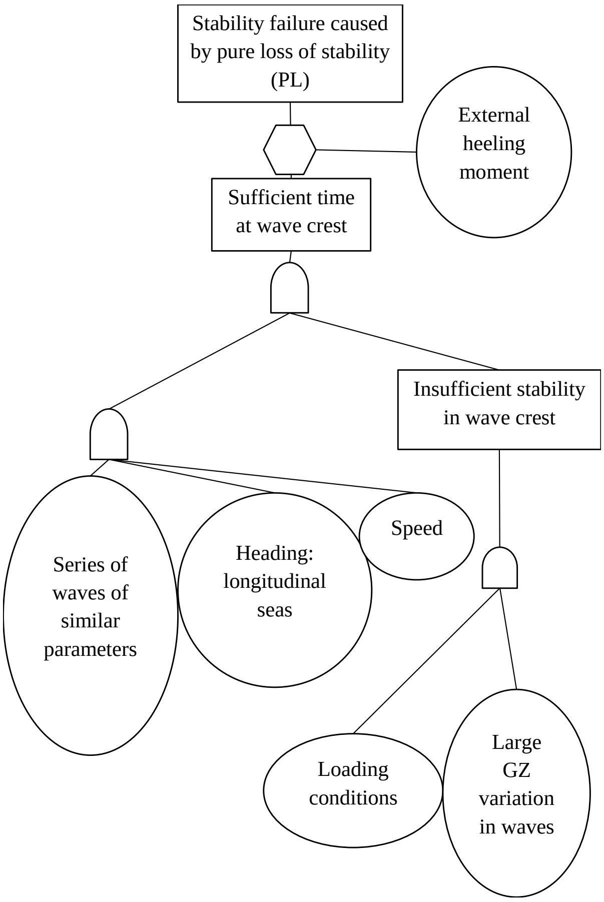


Figure 14: Fault tree for stability failure caused by pure loss of stability (PL)

If a ship has significant bow flares and a large stern overhang, $\overline{GZ}$ curve may experience significant variation if the sufficiently long and steep wave passes by. Decrease of stability while on the wave crest makes a ship 'sluggish' and makes her heeling more under an external heeling moment. When the mid-ship's sections pass the wave crest, stability improves and push–back from the inclined position is stronger. This combination of low and high-stability of "sluggish" heeling and strong push-back may lead to increasing magnitude of rolling if a ship does not have enough roll damping to disperse this additional energy. It is the essence of the amplitude condition of the parametric roll.

Figure 14 shows a fault tree for pure loss of stability. Similar to parametric roll, the pure loss of stability requires a significant variation of stability in waves, thus encounter with a wave of specific parameters is required.

Significant stability variation in a wave is necessary but not a sufficient condition. The KG-value should be high enough to make the stability in wave crest insufficient to withstand an external heeling moment.

The decreased stability state should last long enough, for the external heeling moment to cause a roll angle, exceeding prescribed limit.

Figure 15 shows a fault tree for Dead Ship Condition. As it is clear from its term, the failure mode is initiated by loss of propulsion and steering. The conventional assumption is that the wind turns a ship into a beam or near beam seas position.

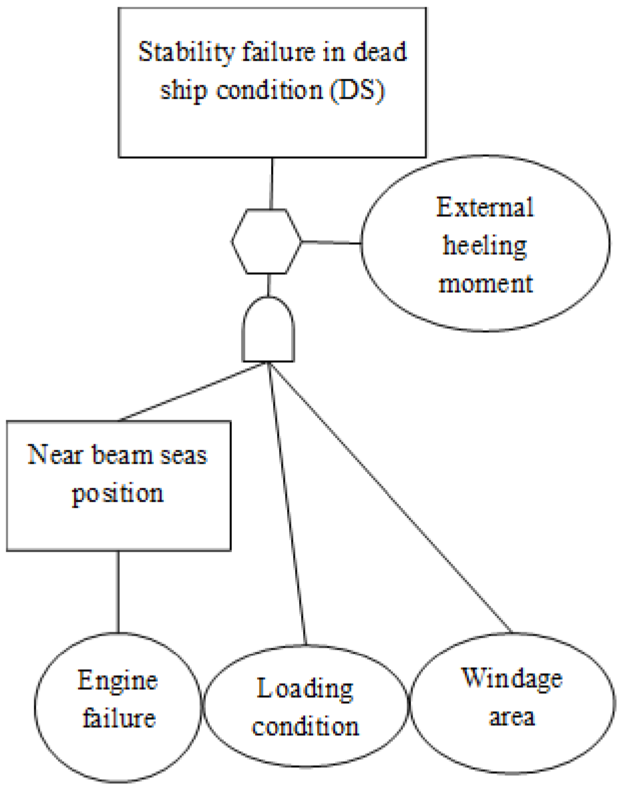


Figure 15: Fault tree for stability failure on dead ship condition (DS)

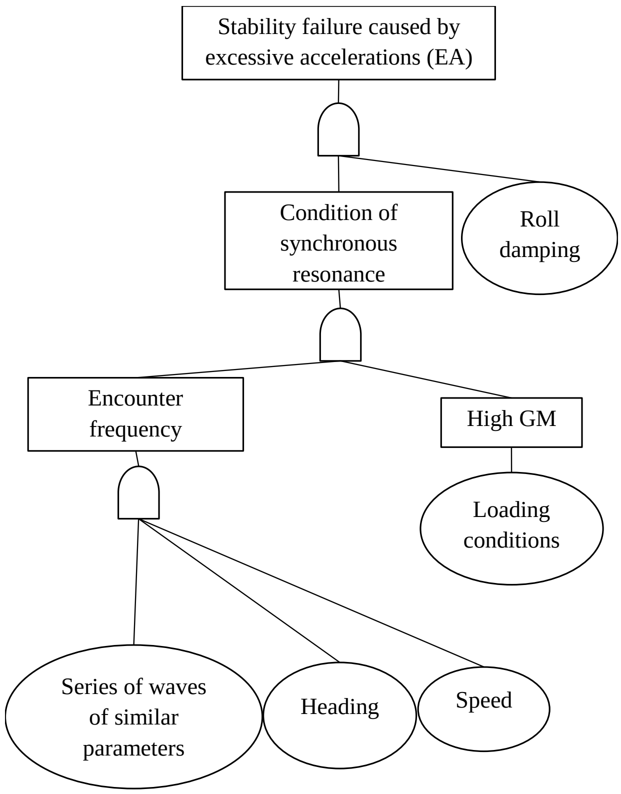


Figure 16: Fault tree for stability failure on excessive acceleration (EA)

Lateral projection of the windage area plays a significant role in the development of stability failure in dead ship condition as the wind heeling moment is one of the principle environmental factors.

As expected loading state with high *KG* value is when a ship is the most vulnerable to stability failure in dead ship condition.

The external heeling moment is created by a wind gust, while a ship is assumed drift under the action of wind and waves. Hydrodynamic drag induced by the drift adds to the heeling actions of the wind.

Waves cause roll motions that may be significantly amplified by synchronous roll resonance when the natural roll frequency is close to the modal frequency of the wave spectrum.

A ship may be vulnerable to excessive acceleration stability failure mode in ballasting loading conditions when GM value is high.

The failure is initiated by an encounter of a series of waves with similar parameters. Speed and heading make the frequency of encounter close to the natural frequency of roll.

A similar value of encounter frequency and roll natural frequency creates a condition of synchronous resonance. If roll damping is not sufficient, the roll angles can increase together with lateral acceleration that is closely correlated with roll angle. The failure occurs when lateral acceleration at a high location (usually wheelhouse) exceeds a prescribed value.

Task 3 of the Terms of References calls for use of the fault tree for the identification of the failures. So, a stability failure (e.g. capsizing or high roll angle) from the full-scale record or numerical simulations can be associated with one of these fault trees. Indeed, more information is available; the more likely adequate fault tree is identified for the observed phenomenon. Many parameters can be useful for this evaluation. For the following consideration, all the parameters are assumed to be available; so, a particular fault tree can to be adapted to the specific case.

If a hull form is available, it can be useful to test the ship according to the level 1 and 2 of IMO SGISC for the four-roll angle-related stability failure modes (that can end in a capsize). Then the vulnerability of the ship will be pointed out for one or the other modes. For some failure modes, the IMO SGISC testing suggests estimating the probability of a large roll angle. Then it will give an indication of the most dangerous heading, speed and waves.

The first step could be related to the relative heading: What is the relative heading just before or during the capsize events?

If the answer is clear (the relative wave heading can be well determined) and can be identified as nearly transverse, head of following, then this first question is useful.

If relative wave heading approximately corresponds to beam seas dead ship condition is a good candidate for the failure mode. A factor, which increases this possibility, is high wind speed. As the stability failure is caused by excessive roll angle, it is expected to occur for the forced roll period to be close to the natural roll period (synchronous roll resonance condition) or for very high waves. The dead ship condition is defined as an event following by an engine failure, but it can be generalized to excessive roll motion caused by synchronous resonance, particularly without forward speed and beam waves.

If relative heading corresponds to approximately head or following waves, there may be several modes of failure. If the heading is head or oblique waves, the most probable mode of failure is parametric roll, which has to be confirmed by the second question.

The second step is related to the speed of the ship. The forward speed has to be compared to wave celerity (when it can be estimated and considered as a good characteristic of the real sea state) and critical speed for the parametric roll. The range of ship speeds characteristic of the parametric roll is given by Spyrou and cited in reference by IMO SGISC. A simple verification for parametric roll possibility is to check if encounter frequency is about twice the natural roll frequency with low roll damping. A development of parametric roll may be expected.

If wave speed is close to instantaneous wave celerity just before stability failure it means that surf-riding occurred. If so, the instantaneous ship speed must be closely analysed in order to determine if the average ship speed is abnormally increased due to the wave (high-run) which is a very good indicator. Looking for high-runs as defined by Kontolefas and Spyrou (2018), as a significant time when the ship's speed is increasing, is useful. Figure 17 from the cited reference show an example of a high-run on a numerical simulation.

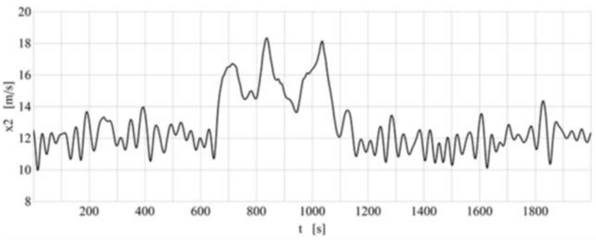


Figure 17: Time history of surge velocity with a high run

Surf-riding is usually not the mere reason for stability failure but very often it is a phenomenon which leads broaching. Broaching happens in following or stern quartering waves, after a surf-riding. Broaching can be identified by the activities of the rudder and the analyses of motions. Surf-riding occurs also for the low frequency of encounter, then the motions are ceased because the ships are "caught" by waves. In this situation, force in the vertical plane are quite important and have a strong effect on motions even at low frequency, then trim is the best indicator for this. Then a constant trim for a long time on high and steep waves is another good indicator of surf-riding.

As to broaching another point to look into is whether the ship loses yaw stability and has difficulties to keep constant her course including effect due to the characteristics of the autopilot. Then analysing yaw motion is a good idea because of the autopilot. Unexpected yaw motion can be observed (large amplitude and/or value). Rudder activity has also to be analysed. Rudder at its maximum value for a long time is a sign that the ship struggles to keep constant the direction, which means that broaching is about to occur. Then broaching occurs because the rudder cannot counteract the yawing moment induced by the wave and the vessel deviates rapidly from its initial heading (let us say 20° as given by Renilson and Tuite, 1998). It is often associated with an increasing roll angle partially due to the rudder heel moment, partially to the reduction of restoring moment and high centrifuge moment (see Figure 18). Surf-riding occurs only on high and steeped waves. The minimum value can be determined following IMO SGISC methodology.

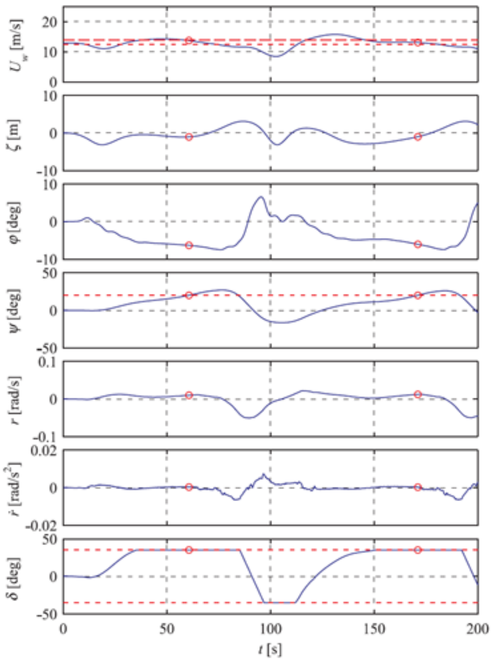


Figure 18: Time traces showing broaching (*Fr = 0.40*, $\Psi_w = 20°$, $H/\lambda = 1/20$, $\lambda/L = 1.04$) from P. de Jong (2025)

Some other checks can also help. If possible, if the natural roll period of the ship just before the failure can be determined and if it is close to twice of the wave encounter period it is a good indicator of Parametric Roll (depending on heading and waves) or a failure similar to Dead Ship Condition, as roll resonance.

Ship speed is also related to the time spent near the wave crest. If the time near the wave crest can be determined to be long enough for a ship to react on an external heeling moment then the stability failure is likely to be pure loss of stability.

The review of the IMO Second Generation intact stability criteria and standards with a particular focus and background for each stability failure mode is prepared as a draft of IMO INF paper to be submitted by ITTC to 8th session of SDC.

The review starts with the probabilistic framework, which is common for all failure modes. Main probabilistic assumptions are discussed, leading to short- and long-term formulations. The short-term formulation assumes constant environmental (wave and wind spectra) and operational (forward speed and relative wave heading) leading to stationary ship response. The long-term formulation accounts for the variability of the environmental and operational condition during the service life of a ship.

Discussion of each failure mode (except for the dead ship condition) includes a short description of relevant stability accidents with references on official investigation reports. The accident description follows a discussion of physical mechanism and relevant mathematical models of stability failure, as well as a literature review.

Review of physics of the stability failure in dead ship condition starts from a discussion of forces acting on a ship in beam seas and the way these forces can be computed. The probabilistic formulation is based on upcrossing theory, so it is given a brief review. Further discussion is focused on equivalent failure angles (used in the level 2 vulnerability criteria) as a method to treat nonlinearity of roll motion in irregular waves, using energy/work balance.

Consideration of excessive acceleration failure mode includes a brief review of the kinematics of a point of a rigid body involved in arbitrary motion. Then the calculation of lateral acceleration is examined as well as specifics of the application of upcrossing theory.

Review of pure loss of stability includes basic dynamics rising form variation of stability in waves. Brief consideration is given to a repeller, a dynamical system with negative stiffness, modelling roll motion of a ship in the case of complete loss of stability on a wave crest. Then probabilistic properties of stability in waves are discussed and it is shown that changes of the $\overline{GZ}$ curve in a wave may be very complex. Grim (1961) effective wave is considered as a way to resolve this complexity.

Review of parametric roll mode of failure starts from the derivation of the Mathieu equation - most basic mathematical model of parametric resonance. Then the solution of Mathieu equation and its properties are considered and Ince-Strutt diagram (graphic depiction of instability zones of the solution) is introduced. The influences of damping and nonlinearity of stiffness are examined; finally, an account of the irregularity of realistic sea waves is addressed.

Discussion of surf-riding and broaching also starts form equation of surge motions as a transition to surf-riding from surging is a precursor of broaching-to. Mathematical modelling of surf-riding equilibrium and its stability is described, and phase plane presentation is introduced. The criterion is based on phase plane analysis and is expressed with the Melnikov function (Melnikov, 1963), which is given a brief review. Finally, mathematical modelling of broaching after surf-riding is discussed as well as probabilistic treatment of stability failure caused by broaching-to in irregular waves.

The document is concluded with a short summary and contains 129 references, covering most of the relevant literature. The document may be especially useful serving as the starting point for the future revisions of the second generation IMO intact stability criteria.

5. RECOMMEDATION ON DEVELOPEING A SET OF PROCEDURES FOR DIRECT ASSESSMENT OF THE SECOND GENERATION IMO INTACT STABILITY CRITERIA (TOR 4)

5.1 Introduction

Direct stability assessment is the top-tier of the second generation IMO intact stability criteria. It is an evaluation of dynamic stability of a ship in waves with the most up-to-date numerical simulation tools, model test or combination of thereof. Currently, direct stability assessment is described in Chapter 3 of the IMO Interim Guidelines on the second generation intact stability criteria, published in Circular 1627 of IMO Maritime Safety Committee (MSC.1/Circ.1627).

The Interim Guidelines formulates objective of the direct assessment (Section 3.1) and gives a definition of the stability failure event (Section 3.2). Requirements for predication of ship motion are formulated in Section 3.3. Requirements for model test are referred to ITTC Procedure 7.5-02-07-04.1 or as amended.

Requirements for numerical simulation tools include statistical validity of irregular wave model (subsection 3.3.2.1 of the Interim Guidelines). Self-repetition effect is one of the most important factors of the statistical validity, as it affects confidence interval of all ship motion estimates made with the model. Avoiding self-repetition effect is addressed in the proposal to develop an ITTC procedure, see Section 2 of this report.

The subsection 3.3.2.2 of the Interim Guidelines contains requirements for modelling of roll damping. Recently updated ITTC procedure 7.5-02-07-04.5 on Estimation of Roll Damping is relevant for these requirements (see Section 6 of this report). A new possible contribution may include an ITTC guidance or a procedure how to avoid duplication in modelling of roll damping. The duplication may be present when wave component of roll damping is included in model test data and internally computed by potential flow numerical simulation tool as a part of diffraction and radiation force and moment. No specific proposal has been developed yet.

The Interim Guidelines address validation of the numerical simulation tools in Section 3.4 of the Interim Guidelines. The validation is defined as "the process of determining the degree to which a numerical simulation is an accurate representation of the real physical world from the perspective of each intended use of the model or simulation". Two phases of the validation process is distinguished: qualitative and quantitative. Developing a guidance or procedure for validation of numerical simulation tools is yet another potential area for ITTC contribution; however no specific proposal has been developed yet.

The Section 3.5 of the Interim Guidelines describes procedures for direct stability assessment. It recognizes the problem of rarity – "when the mean time to stability failure is very long in comparison with the natural roll period that serves as a main timescale for the roll motion process". With the exception of the cases of extremely severe waves, application of sufficient-fidelity numerical simulation tool would be too computationally expletive to estimate of stability failure by direct observation. The solution for the moderate to high waves is statistical extrapolation based on a limited volume of ship motion sample, where stability failure may or may not be observed.

New ITTC procedure for statistical extrapolation has been developed and described in the subsection 5.4 of this report. Proposal for new ITTC procedure for estimation of failure rate by direct observation is placed in subsection 5.2 of this report. A proposal for ne ITTC procedure for statistical validation of extrapolation procedures can be found in subsection 5.3 of this report.

The Interim Guidelines also offers alterative to the solution of the problem of rarity: assessment in design situation and assessment using deterministic criteria. Developing procedures for these methods of assessment is another potential contribution from ITTC; however no specific proposal has been developed yet.

Finally, a future ITTC procedure could address the issue of verification of failure modes, required by the subsection 3.5.2 of the Interim Guidelines. In general, ITTC can play an important role in developing and updating procedures for direct stability assessment as the ITTC members are likely performers of these services for the industry.

5.2 Proposal for Procedure of Estimation of Frequency of Random Events

Purpose of the procedure is to formulation a of estimating a rate of stability failures and its confidence interval based on observed random events in a record of ship motions produced by a model test or numerical simulation. The requirements for the estimation procedure are located in the section 3.5.4 of the Interim Guidelines.

The procedure should use all available data, presented as a set of records of different length. First the autocorrelation function is estimated as recommended by procedure ITTC procedure 7.5-02-01-08. Then the envelope of the autocorrelation function is computed by as a set of absolute values of its peaks. The decorrelation time is evaluated as an instant when autocorrelation function falls below 5% (if such instant cannot be found, the time of the first minimum of the envelope is taken as the decorrelation time).

The next step is counting the events for each record; if there is more than one event within the decorrelation time, only one is counted to preserve independence of the events. The rate of events is estimated as $\hat{\lambda} = n/\sum_i T_i$ where T_i is the duration of a simulation time history or model tank run and n is the total count for independent events. The confidence interval is computed using binomial distribution for the random variable *n* or its normal approximation.

The procedure will also address algorithms applicable to numerical simulation only as mentioned in paragraph 3.5.4.4 of the Interim Guidelines. Theoretical background for the proposed Procedure is available in (Leadbetter et al. 2019).

5.3 Proposal for Procedure "Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions and Loads

The purpose of the procedure is to formulate a process for validation extrapolation methods for time domain numerical simulation of ship motions and loads. The purpose procedure if limited by the establishing the validity of the extrapolation procedure and does not address the validation of numerical simulation tool. Requirements for statistical validation of extrapolation methods are found in the section 3.5.6 of the Interim Guidelines.

The first step of the validation is production of a validation dataset of large volume where statistically sufficient number of failures can be observed. To produce a large sample in a practical time, a mathematical model of reduced complexity can be used. This reduced complexity, however should not compromise the qualitative validation of the mathematical model. A volume-based numerical simulation is one example of mathematical model of reduced complexity (see e.g. Weems and Wundrow, 2013 or Weems et al., 2018). The validation dataset is produced for a number of ship speeds, relative wave headings and sea states.

Direct counting procedure (see section 5.2 of this report) is applied to the validation dataset. The rate of failures, estimated from the validation dataset serves as a "true value" for the statistical validation purposes.

Validation of the extrapolation procedure is performed for 50–100 statistically independent data sets, and evaluated for a number of ship speeds, relative wave headings and sea states. The extrapolation datasets are subsets of the validation dataset. Extrapolation procedure is carried out for each of the extrapolation dataset, see e.g. subsection 5.4 of this report.

A comparison is made between the extrapolation and the "true value" for each extrapolation dataset. The comparison should be considered successful if the extrapolation confidence interval and the confidence interval of "true value" overlap.

Validation should be considered successful if a specified number of individual dataset comparisons were successful (88% for 50 sets, 90% for 100 — may be decreased by an "approximation allowance").

Theoretical background for the validation of the procedure is available from Smith (2019).

5.4 New Procedure "Extrapolation for Direct Stability Assessment in Waves"

New ITTC procedure was developed describing two extrapolation methods for direct stability assessment. Section 3.5.5 of the Interim Guidelines mentions envelope peak-over-threshold (EPOT) paragraph 3.5.5.4.1.1 and split-time method/motion perturbation method (MPM) paragraph 3.5.5.4.1.2 among others. The developed ITTC on extrapolation contains brief theoretical background and application process as well as an example and brief validation results for these two methods. This new ITTC procedure is mean to be updated on the future date by adding description for other extrapolation methods mentioned in the Section 3.5.5 of the Interim Guidelines.

Theoretical background of EPOT and MPM is the extreme value theory, describing probabilistic properties of the largest observation in a sample (e.g. Coles, 2001).

The first extreme value theorem (also referred as Fisher-Tippett-Gnedenko theorem) proves that a distribution of the largest values in a sample of independent observations has a limit in the form of a Generalized Extreme Value (GEV) distribution:

$$\mathrm{cdf}(y) = \begin{cases} \exp\left\{\left(1+\xi\frac{y-u}{\sigma}\right)^{-\left(1+\frac{1}{\xi}\right)}\right\} & \xi \neq 0 \\ \exp\left\{\exp\left(-\frac{y-u}{\sigma}\right)\right\} & \xi = 0 \end{cases}$$

where ξ is a shape parameter, σ is a scale parameter and u is a location parameter. The case $\xi = 0$ is known as Gumbel family of distributions. There are two more particular cases: Fréchet and Weibull families of distributions (when the location parameter has a bound).

Fitting GEV distribution to numerical simulation or model test data, in principle, allows extrapolation beyond the observed values. As required by the first extreme value theorem, the data points must be independent. It is achieved by application of "block maxima" technique. The time series data are separated into independent fragments, "blocks" (e.g. using decorrelation time) and the largest value in each "block" is used to fit the GEV; see example in Wandji (2019).

First application of GEV in the form of Gumbel distribution for dynamic stability in waves was carried out by McTaggart (2000a, 2000b), McTaggart and de Kat (2000c).

The second extreme value theorem (also referred as Pickands-Balkema-de Haan theorem) states that the GEV distribution can be approximated by a Generalized Pareto Distribution (GPD) above a large-enough threshold. That means, a tail of ($y > u$) of any distribution can be approximated with a GPD:

$$\mathrm{pdf}(y) = \begin{cases} \frac{1}{\sigma}\left(1+\xi\frac{y-u}{\sigma}\right)^{-\left(1+\frac{1}{\xi}\right)} & \xi \neq 0 \\ \frac{1}{\sigma}\exp\left(-\frac{y-u}{\sigma}\right) & \xi = 0 \end{cases}$$

$$\mathrm{cdf}(y) = \begin{cases} 1-\left(1+\xi\frac{y-u}{\sigma}\right)^{-1/\xi} & \xi \neq 0 \\ 1-\exp\left(-\frac{y-u}{\sigma}\right) & \xi = 0 \end{cases}$$

where ξ is a shape parameter, σ is a scale parameter and u is a location parameter that here has a meaning of a threshold value for the tail of distribution of y.

The extrapolation for the rate of exceedance is expressed as:

$$\hat{\lambda}(c) = \hat{\lambda}(u)\left(1-\widehat{\mathrm{cdf}(c)}\right)$$
$$= \hat{\lambda}(u)\mathrm{P}(Y > c|Y > u)$$

where $\hat{\lambda}(u)$ is the rate of upcrossing (or down crossing) of the threshold u, which can be estimated directly form the time series (see section 5.2 of this report).

The scale parameter σ is positive, while the shape parameter ξ can be either positive or negative. A negative shape parameter imposes a limitation on the expressions in parenthesis of the equations and formally introduces a right bound to the distribution:

$$\mathrm{pdf}(y) = 0 \; if \;\; y > u - \frac{\sigma}{\xi} \text{ and } \xi < 0,$$

The shape parameter defines the type of tail: heavy, exponential, or light, as shown in Figure 19.

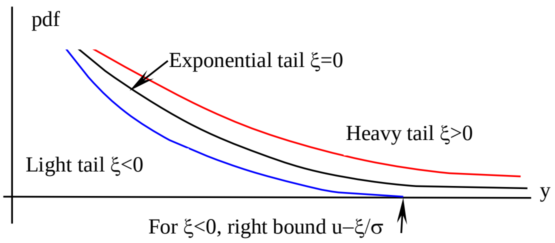


Figure 19: Types of tails per GPD approximation

The peak-over-threshold (POT) method is a generic extrapolation method based on GPD (Pickands, 1975). Similar to the GEV case, application of GPD also required independent data. Ship motion time series is dependent data, so independent data points have to be extracted – "de-clustered". A technique to extract independent data form the ship motion time series is to collect peaks of an envelope, shown in Figure 19, and referred as Envelope-peak-over-threshold (EPOT), see e.g. Campbell et al. (2016). The envelope approach is not applicable to parametric roll data, where decorrelation time can be used (Kim et al. 2014).

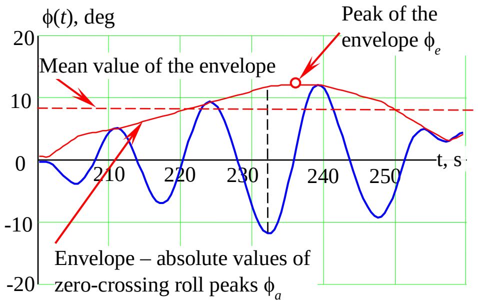


Figure 20: De-clustering using an envelope

Smith (2019) reported results on sample statistical validation of EPOT method for roll, pitch, POT/EPOT method with GPD is entirely data-driven; it is applicable to any ship motion process if sufficient data available. Otherwise, statistical uncertainty may be too large for practical use. One of the manifestations of this large statistical uncertainty may be an inability to complete extrapolation because for $\hat{\xi} < 0$ when the target of extrapolation c lies beyond the GPD bound (Pipiras, 2020). While EPOT with GPD still can be used (see validation example reported by Smith, 2019), better solution with less uncertainty may be achieved with physics-informed extrapolation method.

The roll restoring arm ($\overline{GZ}$) curves of most ships have a limited range of stability, leading to the appearance of an unstable equilibria at the angle of vanishing stability. A peak value of roll angle is quite unlikely to exceed the angle of vanishing stability – ship is likely to capsize. Therefore, the tail of the distribution of roll peaks has a bound near the angle of vanishing stability. The term "peak value" stipulates that the roll angle will reach the peak and then returns back, i.e. no capsizing occur.

All positive ($\overline{GZ}$) curves have maxima. The value of roll resting decreases after the maximum of ($\overline{GZ}$) curve, thus the instantaneous *GM* value is negative after the maximum. There is no instantaneous natural roll frequency after the maximum of ($\overline{GZ}$) curve, so there is no resonance and roll forcing is decreased. Thus, the ship tends to roll slower and spend more time beyond the maximum of ($\overline{GZ}$) curve, leading to increased probability of observing ship in this position, i.e. to heavy tail.

The tail of roll peaks is expected to have a complex structure: a heavy tail right after the maximum of ($\overline{GZ}$) curve, turning into a light tail near the angle of vanishing stability. Figure 21figure **21** illustrates this tail configuration. See Belenky et al. (2019a) for more formal argument and details.

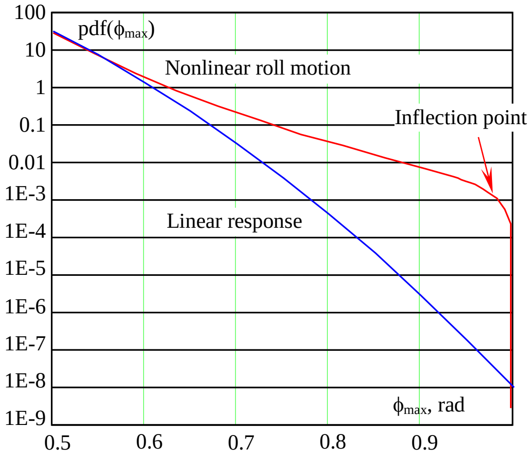


Figure 21: Types of tails per GPD approximation

As the target of extrapolation likely is located beyond the maximum of ($\overline{GZ}$) curve, but not too close to the angle of vanishing stability, the tail of the distribution of roll peaks is supposed to be heavy. When the shape parameter $\xi > 0$ and threshold value $u = \sigma / \xi$, the GPD is equivalent to Pareto distribution with scale $y_m = \sigma / \xi$ and shape $\alpha = 1 / \xi$

$$\text{pdf}(y) = \frac{\alpha y_m^\alpha}{y^{\alpha+1}} = \frac{\alpha u^\alpha}{y^{\alpha+1}}$$

$$\text{cdf}(y) = 1 - \left(\frac{y_m}{y}\right)^\alpha = 1 - \left(\frac{u}{y}\right)^\alpha$$

To fit the Pareto tail, the parameter α has to be estimated and threshold u has to be found. The estimation of the parameter α is done from the data and it has to be treated as a random number. The threshold is found by minimizing of the fitting error. Fitting GPD is similar, but two parameters have to be estimated from the data. As a result, statistical uncertainty for fitting GPD is larger. The decrease of uncertainty is achieved by adding physics information to the statistical model – using heavy tail approximation, based on dynamical considerations. The physics-informed model is applicable within while these physical considerations are valid. i.e. while the target is sufficiently large so the tail can be assumed heavy, see Belenky et al. (2018a).

The heavy tail approximation also implies no significant change of physics. Split-time /motion perturbation method (MPM) complements EPOT with a capability to include changes of physics. The idea of MPM is to compute a metric of likelihood of a stability failure at an instant of crossing of an intermediate threshold and then extrapolate this metric for its critical value corresponding to the imminent failure.

For example to formulate the MPM metric for capsizing, the roll rate at each observed crossing is perturbed until capsizing is observed, see Figure 22. The metric is the difference between the observed roll rate at the crossing of an intermediate threshold and the roll rate that leads to capsizing.

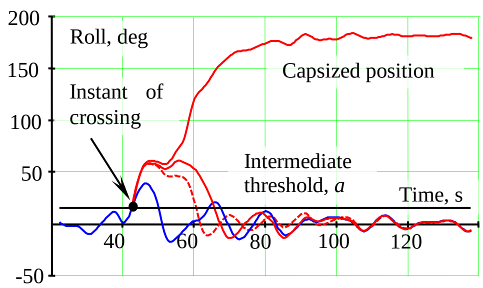


Figure 22: Motion perturbation for computing the capsizing metric

The capsizing metric is a random number showing how likely capsizing is at a given instant of time. It the tail of the MPM capsizing metric is described by exponential distribution:

$$\mathrm{pdf}(y) = \frac{1}{\gamma}\exp\left(-\frac{y-u}{\gamma}\right)$$

$$\mathrm{cdf}(y) = 1 - \exp\left(-\frac{y-u}{\gamma}\right)$$

where γ is the parameter of exponential distribution.

The reason why the tail of the MPM metric is described by exponential distribution is also physical. The MPM metric is the difference between two roll rates. The roll rate is related to a roll damping, which is weak nonlinearity, leading to normal distribution for the roll rate. The distribution of the roll rate at the instant of crossing is described by Rayleigh distribution see e.g. p. 201 of Leadbetter et al. (1983). The tail of Rayleigh distribution tends to exponential tail, see example 1.1.7 of de Haan and Ferreira (2007), while application details are available in Belenky et al. (2018a, 2019a).

The developed procedure covers the following aspects of the EPOT and split-time / MPM methods:

- Abridged version of the theoretical background given above;
- Data requirements for extrapolation
- Data preparation steps
- Fitting the distribution: estimating the parameters and finding the threshold
- Assessment of uncertainty and calculation of confidence interval

Application example is given in the Appendix. Available statistical validation data is reported in Belenky et al. (2018a).

6. FREE ROLL DECAY, FORCED ROLLING AND EXCITED ROLLING TESTS (TOR 5)

Existing ways for the estimation of roll damping include model testing, numerical simulations and the empirical formula approach. Considering the fact that roll damping is one of the most intriguing and difficult research topics in ship dynamics due to its nonlinear nature and the rather complicated viscous effects of the fluid, the experimental approaches are still so far the most reliable. Generally speaking, there are two main types of tests devoted to the determination of roll damping, i.e., roll decay tests and forced roll tests. The latter can be further categorized into the free running forced roll test where the roll moments are designated while the resulting roll motions are measured, and the (semi-) captive forced roll test where the roll motions are designated while the roll moment to generate the motions are measured.

Among them, the roll decay tests are the most widely adopted due to its relative simplicity. The state-of-the-art focus is to reduce human interventions during the testing, i.e, to conduct the roll decay test in a sophisticated manner in order to obtain high-quality data which can withstand the quantitative validation of CFD. One example was already described in Figure 2 and Figure 3 (Hashimoto et al. 2019). By using this kind of purpose-built device, it is possible to repeat the same roll decay test from a fixed angle/attitude and to reduce the uncertainty due to the scattering of initial conditions in roll decay tests.

Free running forced roll tests are based on exciting the ship to continue rolling through internal roll moment generators (RMGs) or external waves, with the ship free to move in all DoF. The requirements on the model and installation are similar to those of the roll decay test. The key difference lies in the instrumentation, especially when the roll moment generator is used. Several types of RMGs are widely used, e.g., the gyroscopic type, the contra-rotating masses type and the moving mass type. The moving mass type seems to be more popular in recent years and has been intensively studied reported by Oliva-Remola, (2018) and Park et al. (2018), see Figure 23.

Captive or semi-captive forced roll tests refer to ships being excited to continuously roll through an externally applied roll moment from an external oscillator between the towing carriage and the model. In such tests, a fixed roll axis is typically being prescribed. Such setup is good for the comparison with numerical simulations, as it can guarantee a pure roll motion, hence reduces the analysis complexity.

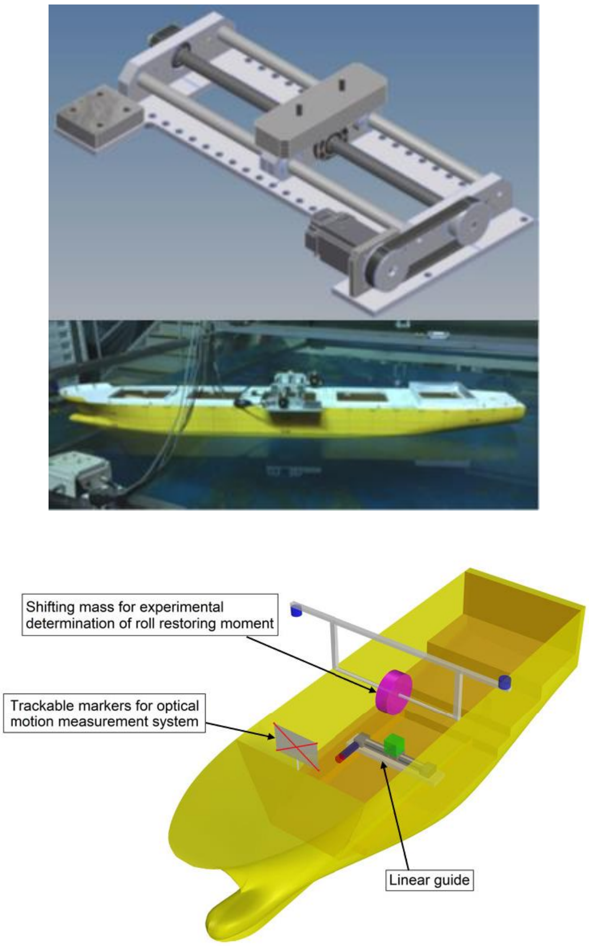


Figure 23: Moving mass type RMGs (Up: Park et al., 2018; Down: Oliva-Remola, 2018)

Same as the free running forced roll tests, special instrumentation is required, which should be able to generate the designated roll motions about the prescribed axis and measure the roll moment simultaneously. These are the so-called forced roll mechanisms. One example of such instrumentation is shown in Figure 24. The mechanism is developed by the Marine Design and Research Institute of China (MARIC), where the forced roll is achieved by a motor while the roll moment is directly measured through a torque sensor

Figure 24: Forced roll mechanism developed by MARIC

Different methods to determine roll damping coefficients from roll decay tests exist. Most of them use the measured amplitude of the time history of rolling motion, as well as the instantaneous time where the amplitude occurs. Commonly used methods to analyse roll decay tests include the following.

Logarithmic decrement method: this method determines the equivalent linear roll damping coefficient by assuming the linear roll differential equation and determines the nonlinear roll damping coefficients by least-squares fitting. The benefits of this methodology are that it may consider nonlinearities in restoring and damping terms, it is simple and also allows to aggregate data from different decay tests prior to performing the least-square fitting, which is more reliable than analysing each decay tests separately and calculating the mean of the determined nonlinear damping coefficients. Further information on this method may be found in Wassermann (2016) and Oliveira et al. (2019).

Froude energy method: this method equates the energy lost to damping in each half-cycle to the work done by the restoring moment during the same period. Further information may be found in Wassermann (2016) and Oliveira et al (2019).

Roberts energy method: this method is based on energy conservation, where the roll decrement is treated as an energy loss function, which is related to the roll damping. Further information may be found in Roberts (1985) and Wassermann (2016).

Least-squares iterative method: this method constitutes a Parameter Identification Technique and is based on the fitting of the numerical solution of the nonlinear differential equation of roll to the time series of the decay test, performing an iterative fitting based on the least-squares method. Further information may be found in Oliveira (2018). It is possible to use a 1-DoF systems but in some cases it can be more efficient to use (Luthy et al. 2021) a complete 6-DoF simulator. This is particularly useful in the case where the damping estimated must be used by this same simulator for simulations in waves. In this case all questions about coupling with others motions, origin of moment and position of centre of rotation are automatically solved.

On the other hand, commonly used methods to analyse forced roll tests include:

The quasi-linear method or Blume's method: the equivalent linear roll damping coefficient is determined from the ratio of the quasi-static heel angle and the measured dynamic roll amplitude, assuming that, at resonance, the inertial part and the restoring part of the equation of motion (approximately) cancel out, directly relating the amplitude of the forcing term at the peak response frequency with the damping term. Further information may be found in Oliveira et al. (2019).

Fourier transformation method: this method uses a Fourier analysis to determine linear and non-linear components of the roll moment which are in phase with the roll velocity (Handschel et al. 2014).

A general comparison of the fore-mentioned test methods for roll damping measurement is given in table 1.

Table 1: General comparison of the test methods for roll damping measurement

Item	Free Decay	Free Running Forced Roll	(Semi-) Captive Forced Roll
Steady roll ampl.	Impossible	Steady	Steadiest
Large roll ampl.	Temporarily	Depends on RMG	Easy to achieve
Forward speed effect	Possible	Possible but difficult	Possible and easy
Memory effect	Not fully included	Included	Included
CFD validation	Medium	Hard	Easy (1-DoF Case)
Roll axis	Real/Time-varying	Real/Time-varying	Prescribed/ Fixed
Time & cost	Cheap	Costly	Costly

Besides the experimental approaches, CFD simulations for roll damping estimation are getting more and more mature and have already become an effective way for roll damping estimation. The following combination of calculation parameters are recommended by Gu et al. (2018a) when simulating free roll decay motion: unsteady RANS equations combined with RNG k-ε / SST k-ω two-equation turbulent model to solve flow field, VOF method to capture free surface, sliding interface technique or dynamic overset mesh technique to compute bodies motions, enhanced wall function to treat near-wall boundary layer. Moreover, it is pointed by Hashimoto et al. (2019) that it is necessary to solve 3-DoF of sway-heave-roll motions or more DoFs for the CFD simulation of roll decay motions. As for the forced roll simulations, Kianejad et al. (2018a) proposed a CFD method based on the harmonic excited roll motion (HERM) technique to compute the roll motion and the roll damping moment of a containership model in different conditions. The influence of excitation frequency, forward speed and DoF at beam-sea and oblique-sea realizations are considered in estimating the roll damping coefficients. The results are validated against model tests, where a good agreement is found.

7. UPDATE PROCEDURE 7.5-02-07-04.5 ESTIMATION OF ROLL DAMPING (TOR 6)

Name of the procedure has been changed from "Numerical Estimation of Roll Damping" to "Estimation of Roll Damping" because the scope of the procedure has been extended from purely numerical estimation based on an empirical formula to include also the relevant experimental approaches (including some IMO methodologies) to obtain the roll damping. Section "2.1 Background equations" is added to give a clearer introduction of the subject, and section "3. Procedure for estimating roll damping from experiments" is added, where sections "3.1 Roll decay tests in calm water", "3.2 Free running forced roll tests", "3.3 (Semi-) Captive forced roll tests" are discussed. A new section of "4.3 Simplified Ikeda's method" is added in the updated procedure. Section "3.3 Decay coefficients" in the original procedure is deleted and rewritten as section "3.1.7 Data reduction and analysis", where available methods are summarized into four categories: (1) Logarithmic decrement method; (2) Froude energy method; (3) Roberts energy method; (4) Least-squares iterative method. The updated new procedure is more comprehensive compared with the original version.

8. UPDATING THE GUIDELINE 7.5-02-07-04.3 FOR PARAMETRIC ROLL (TOR 7)

The Guidelines 7.5-02-07-04.3 (Predicting the Occurrence and Magnitude of Parametric Rolling) was updated towards Recommended Procedure. The updated procedure was structured in three levels, similar to the second generation IMO intact stability criteria. Each level corresponds to different fidelity and complexity of methods described. An extensive example has been added as an Appendix.

The purpose of the procedure is to provide a detailed guidance on assessment occurrence and magnitude of parametric roll using analytical, semi-analytical and numerical methods.

A review of other procedures and guidances produced by IMO and class societies has been added to the introduction along with appropriate references. Brief explanation of the new structure of the procedure has been included as well.

The level 1 section starts from the description of the simplest generic mathematical model of ship rolling that allows parametric resonance. A review of semi-analytical and continuation methods have been added. The semi-analytical methods are based on certain functional representation of the expected solution. The result is usually presented in a form of an algebraic equation that is to be solved numerically. A continuation method is completely numerical, based on the “predictor/corrector” scheme. The continuation methods are known for their efficiency. The main advantage of the semi-analytical and continuation methods is that they can find unstable solutions as well as stable once. While unstable solution cannot be realized in the time-domain or in the real world for any significant amount of time; they are very useful as they reveal the structure of phase space.

The level 2 method is essentially simplified method of time-domain simulation. This is a mostly new section of the Procedure. Three different mathematical models are considered: 1-DoF, 3-DoF and 6-DoF.

The single DoF model uses precomputed $\overline{GZ}$ curve in wave presented as a function of wave frequency and height as well as a position on the wave and roll angle. Roll damping can include quadratic and cubic terms or roll velocity. The solution of the roll equation is carried out numerically. Solution in irregular waves is not considered, as it can be done in a simpler way using the 3-DoF model.

Pre-calculation of the $\overline{GZ}$ curve in wave is not recommended for 3-DoF equations of motions, as the volume of data may be too large. Instead the restoring moment can be computed as a part of inseparable hydrostatic and Froude-Krylov force/moment. Calculation hydrostatic and Froude-Krylov force/moment is carried out by integration of hydrostatic and wave pressures over the instantaneous submerged part of the hull. As a fast alternative (that may be useful for irregular waves) the hydrostatic and Froude-Krylov force/moment can be computed through the instantaneous submerged volume and coordinates of its centre (Weems et al. 2018). As it was already mentioned, usage of the 3-DoF model with pressure- or volume–based hydrostatic and Froude-Krylov force/moment is equally simple in regular or irregular waves.

Damping, diffraction and radiation are added in the 3-DoF model in a form of coefficients as it would be done with any other system of ordinary differential equations. The 3-DoF-system can be upgraded to the all 6-DoF model using manoeuvring coefficients. Influence of surging on parametric roll may be important.

The level 3 assessment is geared to use advanced hydrodynamic simulation tools. The updates give a specific description of recommended formulations used the simulation tools with known to work well for predication of parametric roll. These include body-nonlinear formulation for Froude-Krylov and hydrostatic forces/moments, body-nonlinear or body-linear formulation for diffraction and radiation, coefficient-based models for viscous-related forces/moment and use of 3- to 6-DoF dynamic solvers.

Combination of the internal calculation of radiation with coefficient-based models for viscous-related terms (roll damping and manoeuvring) may represent a challenge. If the viscous-related coefficients were obtained from a model test or CFD calculation with the free-surface, the wave effect will be included twice. The updates include recommendation how to correct these coefficients to avoid double counting.

The updated procedure covers choice of conditions for simulation in regular and irregular waves. Particular attention is paid to post-processing results of assessment of parametric roll in irregular waves. Caution is raised for long de-correlation time, typical for parametric roll that may affect assessment of SSA as recommended by the procedure 7.5-02-01-08. Capsizing observation are addressed separately.

The appendix includes example of prediction of occurrence and magnitude of parametric roll, using all three levels. C11-class containership, known for being vulnerable to parametric roll (France et al. 2003), is used as a sample ship. The appendix also addresses some practical calculation issues. In particular, the effect of inclusion of weathertight volume into stability-in-waves calculation is discussed. While weather-tight volumes are not included in the static stability calculation, there is a rational reason to consider them for dynamic stability. Time, while these volumes are submerged, is too short for them to be flooded due to dynamic nature of the phenomenon.

The results of calculation in regular waves are presented as a dependence of the magnitude of parametric roll on the circular frequency of wave for zero forward speed, see e.g. Figure 25. A plot like that shows both occurrence and magnitude of parametric roll.

For the level 1, the example includes a demonstration of the effect of cubic vs 5th-order polynomial fit of the calm-water stability curve on the occurrence and magnitude of parametric roll. While there is almost no effect of the polynomial order on the frequency interval of parametric roll occurrence, some effect was observed for the magnitude, see Figure 25.

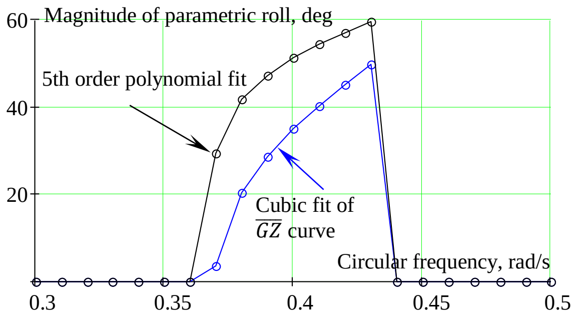


Figure 25: Magnitude of parametric roll as a function of the wave frequency

For the level 2, the example includes a demonstration of the effect of the inclusion of the weather-tight volume, using 1-DoF model. As it is shown in Figure 26, inclusion of the watertight volumes only may lead to conservative results in terms of the magnitude but has a little effect on occurrence.

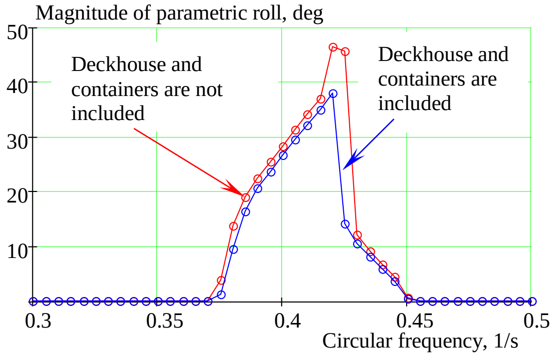


Figure 26: Magnitude of parametric roll by numerical integration of 1-DoF roll equation

The level 2 example also includes a demonstration of the influence of heave and pitch on magnitude and occurrence of parametric roll, shown in Figure 27. The 1-DoF solution seems to be non-conservative in the considered case.

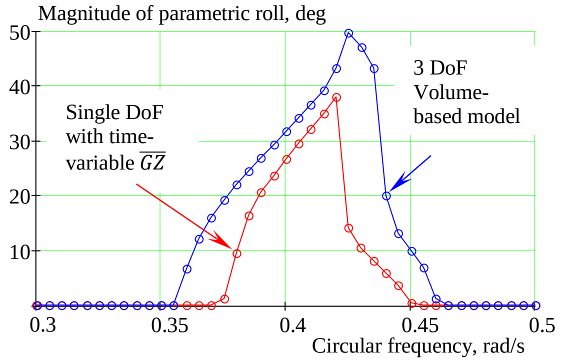


Figure 27: Magnitude of parametric roll. Weather-tight volume is included

For the level 3, the example includes results in regular and irregular waves. Similar to the level 2 cases, the regular wave calculations are presented as a magnitude vs. frequency, see Figure 28. Comparing all four magnitude curves presented in Figure 25 through Figure 27, one can see that the methods on all three levels agree on the frequency interval of occurrence of parametric roll. In general, prediction of magnitude seems to be more conservative from the level 1 methods and the least conservative from the level 3 methods. The consistency between the levels on magnitude seems to be reasonable in the considered example.

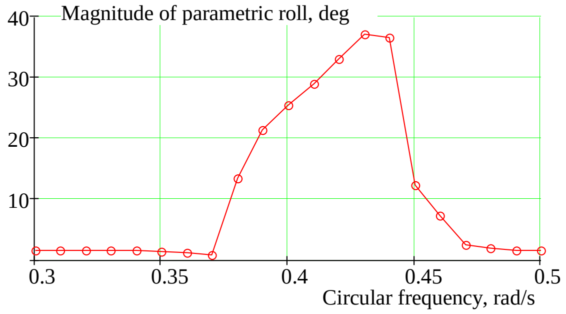


Figure 28: Magnitude of parametric roll computed with LAMP-2 (Shin et al. 2004)

To assess magnitude of parametric roll in irregular waves, the procedure 7.5-02-01-08 has been applied to estimate the SSA. Following the recommendation of Reed (2019b) 20 half-hour long records were generated with LAMP-2 (Shin et al. 2004). The SSA was estimated by direct counting as an average of 1/3 largest peaks, following recommendation of in the subsection 3.2.2 of the Procedure 7.5-02-01-08. The data acquisition process is illustrated in Figure 29: mean-crossing peaks are found (shown as circles), sorted and the 1/3rd largest values collected (shown as squares).

To compute confidence interval of estimated SSA, autocorrelation of 1/3rd largest peaks needs to be estimated. The estimate of autocorrelation function of 1/3rd largest peaks is computed as directed by the section 3.2.2 of the Procedure 7.5-02-01-08 and is shown in

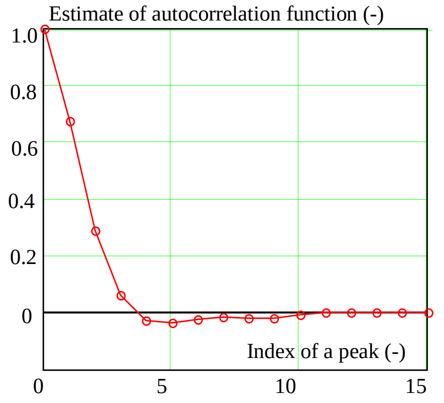


Figure 30. Note, that the estimate of autocorrelation function of the largest 1/3rd peaks is computed for a number or an index of a peak, rather than a time lag. The estimation of SSA yielded 22.5°±0.5° for the significant wave height 3.5 m and mean zero-crossing period of 14 seconds.

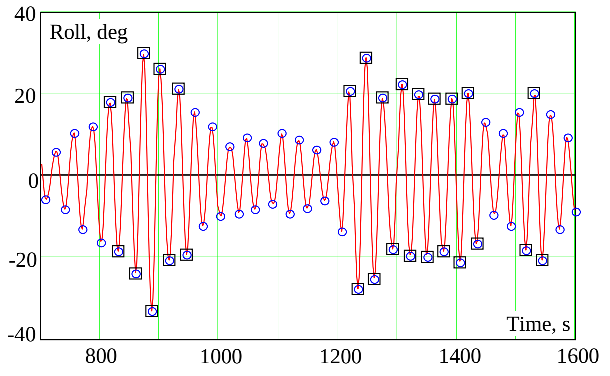


Figure 29: Data acquisition for SSD: mean-crossing peaks (circles), 1/3rd largest peaks (squares)

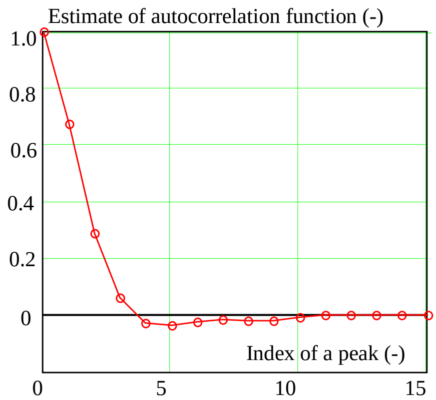


Figure 30 Estimate for the auto-correlation function for 1/3rd largest peaks of roll motion

The appendix contains an example of treating capsizing events as described in the updated procedure. The weather-tight volumes (containers and a deckhouse) were not included and significant wave height was increased up to 9 m, while mean zero-crossing period remained 14 s. SSA estimate was 40.1°, the upper boundary of confidence interval was 40.9° and the lower boundary of confidence interval 39.4°.

9. UPDATE PROCEDURE 7.5-02-07-04.4 NUMERICAL SIMULATION OF CAPSIZE BEHAVIOUR OF DAMAGED SHIPS IN IRREGULAR BEAM SEAS (TOR 8)

The update of the Guideline 7.5-02-07-04.4 on "Numerical Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas" included a number of corrections and addition of references to published original contributions. More specifically, the modelling methods for the free surface in tanks and flooding open spaces were added. A reference to technological innovations in the area of active buoyancy and stability recovery systems which may affect the permeability of a space over time is now included. Such systems may provide significant improvements to the survivability of a ship in the future. Furthermore, the concepts of the capsize band, the capsize rate, the critical wave height and the time to capsize (TTC) were included as they are important attributes of the capsizal behaviour.

Ongoing research work (Boulougouris et.al. 2020), a coupling of the TTC with the time available to evacuate (TTE) and fusing real-time sensor information, will allow the development of real-time risk assessment during uncontrolled flooding incidents. Recent work and findings on the use of CFD methods on the prediction of the behaviour of the damaged ship in waves have shown the increasing interest for such applications. However, the challenges of high computational power and time are still present and the need for expertise and attention to the quality of the mesh is still evident. This suggests that these methods are not ready yet for general use in the prediction and analysis of stability issues. Nevertheless, they provide valuable input for hybrid or blended methods and their performance continues to improve, presenting future opportunities.

10. : DEVELOP/SUGGEST A METHOD FOR ESTIMATING TIME TO CAPSIZING AND / OR SINKING (TOR 9)

The time interval between the start of the flooding of the vessel and its final capsizal determines the "time to capsize" (TTC). This is a significant output from the time domain simulations. Several researchers have proposed concepts such as "survival time" (Jasionowski, 1999) or "time to sink" (van Veer et al., 2002). Jasionowski et al. (2002) proposed the consideration of individual waves or groups as an integral element of the capsizing process. The capsize event is identified from the presence of the incidence of the critical groups. TTC is then calculated by the statistical analysis of the results.

Van Veer et al. (2002) referred to the time required to reach specific SOLAS static criteria such as a maximum roll of 30°, mean roll angle of 20° within 3 min and mean roll angle of 12°. Spanos et al. (2007) distinguish between TTC and the "time to ship loss" that corresponds to the loss of adequate floatability or stability.

Valanto (2006) proposed alternatively the term "time to flood", representing the time from the initiation of the water ingress and the steady-state ensuing progressive flooding.

Atzampos (2019) underlines that TTC is fundamentally linked to the critical wave height (HScrit) concept since it forms an upper boundary of the area where it is likely to observe capsizes. That conceptually forms an asymptote of the TTC distribution (see Figure **21**). Generally, TTC will decrease with the increase of the encountered wave height. Therefore, the TTC is inversely proportional to the difference between HScrit and the actual sea state.

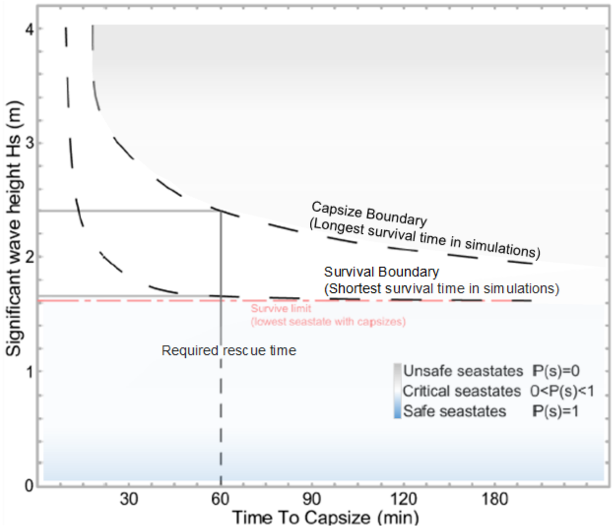


Figure 31: Capsize and survival boundary concept with indication of the safe and unsafe regions with respect to change of the Time to Capsize as a function of the significant wave height. (Atzampos, 2019)

Monte Carlo sampled numerical simulations are used to determine the relationship between the TTC and the survivability. Spanos and Papanikolaou (2012) compared the TTC with the IMO stipulated time for the orderly abandonment. Atzampos (2019) used a direct approach based on time-domain simulations to estimate the expected probability of survival and the TTC for a given group of damages characterised by random damage locations, damage extent and sea-states. The direct approach derives from the non-zonal approach presented by Bulian et al. (2018) and Zaraphonitis et al. (2013). Instead of using the probabilistic survivability index (s-index), a numerical simulation is performed.

11. CONTINUE THE IDENTIFICATION OF BENCHMARK DATA FOR VALIDATION OF STABILITY IN WAVES PREDICTIONS (TOR 10)

The list started by the previous ITTC in China was updated. A new column was added in order to mention the ITTC Recommended Procedures in relation to each benchmark data. The list is available on request.

There is an ITTC guideline about benchmarking, 4.0-01, but the objectives were not to describe the data collection. There is no available description of a good benchmark in terms of minimum data needed or results given. In particular, it should be stated how numerical benchmark, without comparisons to experiments, could be considered or not.

12. RECOMMENDED PROCEDURES FOR INCLINING TESTS (TOR 11)

A new Term of Reference was added to the committee. Develop a procedure for undertaking inclining tests at full scale include estimates of the measurement uncertainty. Originally it was given to the Seakeeping committee (TOR 10) but finally it was assigned to Stability in Waves Committee to liaise with the Seakeeping Committee.

The need of an update procedure was made clear by the fact that the post processing was always the one used more than two centuries ago an could be improved by the modern numerical capabilities. Dunworth (2013, 2014, 2015), Wilezynski (1995), Smith et al. (2016) and Karolius and Vassalos (2018) present a new methodology to improve the accuracy of the estimation of the position of the centre of gravity which is recommended in the proposed procedure.

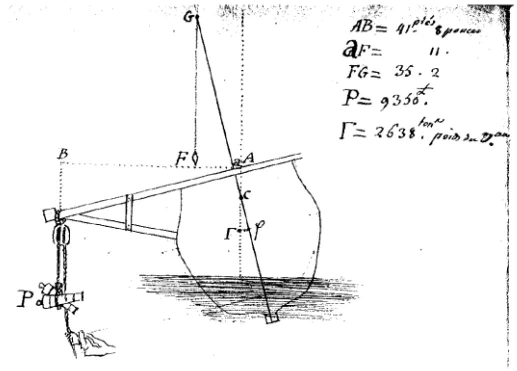


Figure 32: First referenced inclining experiment in 1748, according Nowacki and Ferreiro (2003)

This procedure established by the committee is the first step because it doesn't take into account the whole process of the determination of the vertical position of the centre of gravity of a real ship for all loads cases. In particular, the procedures is concentrated to the evaluation of the characteristics of the ship during the tests and then doesn’t mentioned the inventory, usually performed before “official” inclining test by a classification society or the extrapolation to others loads case as full loads.

In the procedure, a chapter is dedicated to uncertainties. It is noted that the calculation of the final uncertainty on the *KG* can be carried out with simple methods, including a linear regression of the processing graph, but is a function of the building (presence and number of non-empty capacity), means of inclination used (moving mass or ballasting) and of the instrumentation used (pendulum or inclinometer). A table provided a non-exhaustive list indicating the classic uncertainties usually taken into account for different parameters and means of measurement.

13. IMO LIAISON

The ITTC Stability in Waves Committee representatives attended SDC 6 and SDC 7.

At SDC 6, 4 to 8 February 2019, the ITTC Stability in Waves Committee representatives participated in the meeting of the Expert Group on Intact Stability. Much of the effort of the 2008 IS Code Expert Group focused on the finalizing of the Second Generation Intact Stability Criteria. One of the central issues for discussion was the level of maturity of the vulnerability criteria. Based on extensive sample calculations, it was concluded that vulnerability criteria for parametric roll and for surf-riding/broaching were ready for test application. Multiple inconsistency cases were observed for vulnerability criteria for the rest of failure modes: pure loss of stability, excessive acceleration and dead ship condition. Also it was not clear how the vulnerability criteria for dead ship condition that will have a recommendatory status in the near future will be used together with mandatory weather criterion, Paragraph 2.3 of Part A of the 2008 IS Code. The Expert Group recommended and subcommittee has agreed to go ahead and finalize the vulnerability criteria for all 5 modes of failure, but with understanding that the current level of maturity will be properly reflected in the final documents as well as the relationship between mandatory and recommendatory criteria.

The Expert group has considered in details and finalized drafts for three documents making the mainstay of the IMO Second Generation Intact Stability Criteria:

- Draft interim guidelines on the specification of direct stability assessment procedures, in annex 1 of SDC 6/WP.6
- Draft interim guidelines for the preparation of operational limitations and operational guidance in annex 2 of SDC 6/WP.6
- Draft interim guidelines on vulnerability criteria for the second generation intact stability criteria in annex 2 of SDC 6/WP.6

The expert group agreed that these documents contain all necessary technical information and require editorial work by the

Intersessional Correspondence Group. The final editing (SDC 7/WP.1) was done by the Drafting Group at SDC 7 in 2020. Upon completion, and subcommittee has forwarded the draft to Maritime Safety Committee (MSC) for their approval and publication in a form of MSC Circulars for test application by the Maritime Industry

At SDC 7, 3 to 7 February 2020, the ITTC Stability in Waves Committee representatives participated in the meeting of the Drafting Group on Intact Stability. Much of the effort of the Drafting group focused on the finalizing of Interim Guideline on the Second Generation Intact Stability Criteria.

The central issues for discussion were finalizations of draft MSC circular and the Interim Guidelines on the Second Generation Intact Stability Criteria.

The Drafting group has considered in details and finalized two documents:

- Draft MSC circular, in annex of SDC 7/WP.6
- Interim guidelines on the Second Generation Intact Stability Criteria, in annex of SDC 7/WP.6

The Maritime Safety Committee on its 102nd session (4 to 11-th November 2020) has approved the Interim Guidelines on the Second Generation Intact Stability Criteria. The Interim Guidelines was published as an Annex to MSC.1/Circ.1627.

The Drafting group recommended that the Intersessional Correspondence Group develop the draft Explanatory notes on the Second Generation Intact Stability Criteria coordinated by Dr. Umeda, Japan. The subcommittee agreed with this recommendation and created the Correspondence group. The final editing is expected to be done at SDC 8 in 2021. However, due to the COVID-19, SDC 8 has been postponed until 2022.

This IMO development is well aligned with a number of ITTC aims, making ITTC participation in this development very relevant. In particular, we start to try Interim Guideline on the Second Generation Intact Stability Criteria. The experience gained in implementing the Interim guidelines is very important for ITTC, so it will continue to stimulate improvement of methods for numerical modelling of extreme ship motions with model experiments. In pursue of this aim ITTC has a chance to have a positive impact on this international development that may improve ITTC's stance.

14. CONCLUSIONS AND RECOMMENDATIONS

14.1 Technical conclusions

(1) A survey of literature for new experimental techniques has been conducted. Several recent advancements have been identified. Among them is the new method of measurement of roll damping, where the motion is excited by moving weights. Updated publications describe the development, focused on decreasing cost of conducting an experimental assessment of stability in waves, by using regular wave or a fixed set of wave groups. Another aspect of experimental stability assessment in waves, reflected in the literature is using modelling of wind for stability assessment in dead ship condition.

Following the tendencies of the previous reporting period, CFD application continues to be of interest. High computation cost still prevents use CFD directly for capsizing simulation, however, use of CFD as a "numerical tank", to characterize vortexes and some other forces, seems to become more frequent. Reliable assessment of the uncertainty of CFD-included solution may be the next technical challenge.

(2) The central event of the reporting period is a formal completion of the development of the second generation of IMO stability criteria on the 7th session of the IMO Subcommittee on Ship Design and Construction (SDC 7). The second generation of IMO intact stability criteria covers 5 failure modes: dead ship condition, excessive accelerations, pure loss of stability, parametric roll and surf-riding / broaching-to. All these modes are directly relevant to stability in waves; excessive accelerations are also relevant to seakeeping while broaching is also relevant to manoeuvring in waves. To avoid unnecessary costs, the assessment can be done in three different levels of complexity. Increase of complexity (and cost) of application is meant to be related to decrease of conservatism (if a ship found not to be vulnerable to a particular mode of failure, using lower complexity criteria, there is no need for further assessment). The second generation intact stability criteria also include operational measures, as not all the stability-in-waves problems can be addressed during the design. The description of the second generation criteria and operational measures are included in interim guidance for trial application, issued by the Circ. 1627 of the IMO Maritime Safety Committee.

(3) The most technically complex part of the second generation intact stability criteria is the direct stability assessment. The core of the direct stability assessment is a state-of-the-art numerical simulation of extreme ship motions in severe weather conditions. As direct stability assessment may require numerical simulation of ship motion in irregular waves in time domain, the resulted time histories should be of sufficient length to apply statistical processing. The speed of calculation becomes an important factor, thus emphasizing the use of potential flow and hybrid solvers. Correct statistical modelling of encounter waves is a key technology for correct statistical estimates. In particular, the self-repeating effect is a concern.

(4) Direct stability assessment requires estimation of the statistical frequency of stability failures. If a sufficient number of stability failures can be observed during numerical simulation, direct counting procedure can be applied. The key technologies are an assurance of independent of counted events and assessment of statistical uncertainty of the estimate.

(5) If a sufficient number of stability failures cannot be observed during numerical simulation, methods of statistical extrapolation are meant to be used. Four methods are mentioned in MSC.1/Circ.1627: extrapolation over wave heights, envelope peak over threshold (EPOT), split-time/ motion perturbation (MPM) and critical wave method. The committee has developed a new draft ITTC procedure that contains EPOT and split-time MPM methods with the view of further extension of the procedure, once more information becomes available. Another key technology is a validation of extrapolation methods. There are many other technical challenges associated with the deployment of the direct stability assessment as a regular service. Towing tanks are in a good position to develop and offer this service as an extension to the currently available model tests and numerical simulations. Establishing recommended procedures to support these new services should be made a priority of the work of the Stability in Waves Committee for the next ITTC period.

(6) The committee has updated the ITTC recommended procedure for roll damping 7.5-02-07-04.5, covering both numerical and experimental methods. Simplified Ikeda method was added to the procedure. The committee has also made substantial updates to the ITTC Recommended Guideline 7.5-02-07-04.3 “Predicting the Occurrence and Magnitude of Parametric Rolling” towards a Recommended Procedure. The procedure was given a tiered structure similar to IMO second generation intact stability criteria. The level 1 includes formulae for approximate assessment, while level 2 contains a description of numerical techniques that can be used without specialized software. Finally, level 3 is focused on the assessment of parametric roll with

numerical simulations. Example of calculations for all three levels was included as an appendix.

(7) In the Guideline 7.5-02-07-04.4 “Numerical Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas” a number of corrections to has been implemented and additional references to published original contributions were added. The modelling methods for the free surface in tanks and flooding open spaces have been added. A reference to the use of active buoyancy and stability recovery systems which may affect the permeability of a space over time is now included. Such systems may provide significant improvements to the survivability of a ship in the future. Furthermore, the concepts of the capsize band, the capsize rate, the critical wave height and the time to capsize (TTC) were included as they are important attributes of the capsizal behaviour. Recent work and findings on the use of CFD methods on the prediction of the behaviour of the damaged ship in waves have shown the increasing interest for such applications. However, the challenges of high computational power and time are still present and the need for expertise and attention to the quality of the mesh is still evident. This suggests that these methods are not ready yet for general use in the prediction and analysis of stability issues. Nevertheless, they provide valuable input for hybrid or blended methods and their performance continues to improve, presenting future opportunities

(8) The committee has developed a new draft ITTC recommended procedure on Inclining Tests. The procedure covers environmental and ship conditions, survey, displacement measurements, the actual tests, post-processing and uncertainty assessment.

(9) The committee confirmed the need of a list of good benchmark and a storage place for available data, at least for ITTC benchmarks. It is suggested that this effort should be done commonly by all committees for more beneficial result seed of task common to all groups, need of a unified format and a web site to depose data.

(10) The committee has,

- Reviewed ITTC Recommended Procedure 7.5-02-01-08, “Single Significant Amplitude and Confidence Intervals for Stochastic” and found that there is insufficient data to propose any changes at this moment;
- Reviewed ITTC Recommended Procedure 7.5-02-05-07, “Dynamic Instability Tests” from high speed marine vehicles domain and found no changes necessary at this moment;
- Reviewed ITTC Recommended Procedure 7.5-02-07-04.1, “Model Tests on Intact Stability” and found no changes necessary;
- Reviewed ITTC Recommended Procedure 7.5-02-07-04.2, Model Tests on Damage Stability in Waves and found no changes necessary;
- Reviewed ITTC Recommended Guideline 7.5-02-07-04.3, “Predicting the Occurrence and Magnitude of Parametric Rolling” towards a Recommended Procedure and submitted updated document;
- Reviewed ITTC Recommended Procedure 7.5-02-07-04.4, “Numerical Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas” and submitted updated document;
- Reviewed ITTC Recommended Procedure 7.5-02-07-04.5, “Numerical Estimation of Roll Damping” and submitted updated document;
- Reviewed ITTC Recommended Procedure 7.5-03-02-03, “Practical Guidelines for ship CFD application” and proposed changes;
- Submitted a new ITTC recommended procedure and two proposals for new ITTC recommended procedures in support of direct stability assessment within Second generation IMO intact stability criteria;
    - Developed and submitted a new ITTC Procedure “Extrapolation for direct stability assessments in waves, including split-time and POT/EPOT

methods";
  - Submitted a proposal for a new ITTC Procedure "Estimation of Frequency of Random Events by Direct Counting";
  - Developed and submitted a proposal for a new ITTC Procedure "Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions";
- Submitted a proposal for a new ITTC Procedure "Guidance on Avoiding self-repeating effect in time-domain numerical simulation of ship motions";
- Submitted a proposal for a new ITTC Procedure "Computational procedure for instantaneous $\overline{GZ}$ curve during time-domain numerical simulation in irregular wave";
- Submitted a new ITTC Recommended Procedure "Inclining Tests";
- Developed draft of IMO INF paper on the review of SGISC submitted by ITTC to the 8th session of SDC.

14.2 Recommendations to the Conference

- Adopt the updated ITTC Procedure 7.5-02-07-04.5 "Estimation of Roll Damping";
- Adopt the updated ITTC Procedure 7.5-02-07-04.3 "Predicting the Occurrence and Magnitude of Parametric Rolling";
- Adopt the updated ITTC Recommended Procedure 7.5-02-07-04.4, "Numerical Simulation of Capsize Behaviour of Damaged Ships in Irregular Beam Seas";
- Adopt the updated ITTC Recommended Procedure 7.5-03-02-03, "Practical Guidelines for ship CFD application";
- Adopt the new ITTC Recommended Procedure, "Inclining Tests".
- Adopt the ITTC Recommended procedure "Extrapolation for direct assessment stability in waves";
- Develop new ITTC Recommended Procedure "Statistical Validation of Extrapolation Methods for Time Domain Numerical Simulation of Ship Motions and Loads";
- Develop new ITTC Recommended Procedure, "Guidance on Avoiding Self-Repetition Effect During Numerical Simulation of Ship Motions";
- Develop new ITTC Recommended Procedure " Estimation of Frequency of Random Events";
- Develop new ITTC Recommended Procedure "Predicting the Instantaneous $\overline{GZ}$ Curve during Time-Domain Numerical Simulation";
- Update ITTC Procedure 7.5-02-01-08 "Single Significant Amplitude and Confidence Intervals for Stochastic Processes" when new information becomes available;
- Submit IMO INF paper on the review of SGISC to 8th session of SDC.

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15.2 Nomenclature

BR	Broaching-to
CFD	Computational Fluid Dynamics
CRNAV	Cooperativ Research NAVies
CTO	Centrum Techniki Okrętowei - Maritime Advance Research Centre
Circ.	IMO Circular
DoF	Degree of Freedom
EA	Excessive Acceleration
EPOT	Envelope Peaks over Threshold
EU	European Union
FORM	First Order Reliability Method
FTA	Fault Tree Analysis
FORM	First Order Reliability Method

GEV	Generalized Extreme Value
GPD	Generalized Pareto Distribution
HERM	Harmonic Exciting Roll Motion
IMO	Int'l. Maritime Organisation
2008 IS Code	Code on Intact Stability 2008
ISSW	Int'l Ship Stability Workshop
ITTC	Int'l Towing Tank Conference
MPM	split-time/ Motion Perturbation Method
MSC	Maritime Safety Committee of IMO
NSC	Naval Ship Code, published by NATO as ANEP-77
ONR	US Office of Naval Research
OMAE	Int'l Conference on Ocean
PL	Pure Loss of stability
POT	Peak-Over-Threshold method
PR	Parametric Roll
RANS	Reynolds Average Navier Stokes
RPS	Revolution per Second
RNG	Renormalisation Group (related to CFD)
SDC	Sub-Committee on Ship Design and Construction of IMO
SGISC	Second Generation of Intact Stability Criteria of IMO
SOLAS	International Convention for the Safety of Life at Sea
SSA	Single Significant Amplitude
SST	Share Stress Transport (related to CFD)
TOR	Terms of Reference
TTC	Time To Capsize
TTE	Time available To Evacuate
VCG	Vertical Centre of Gravity
VOF	Volume of Fluid method